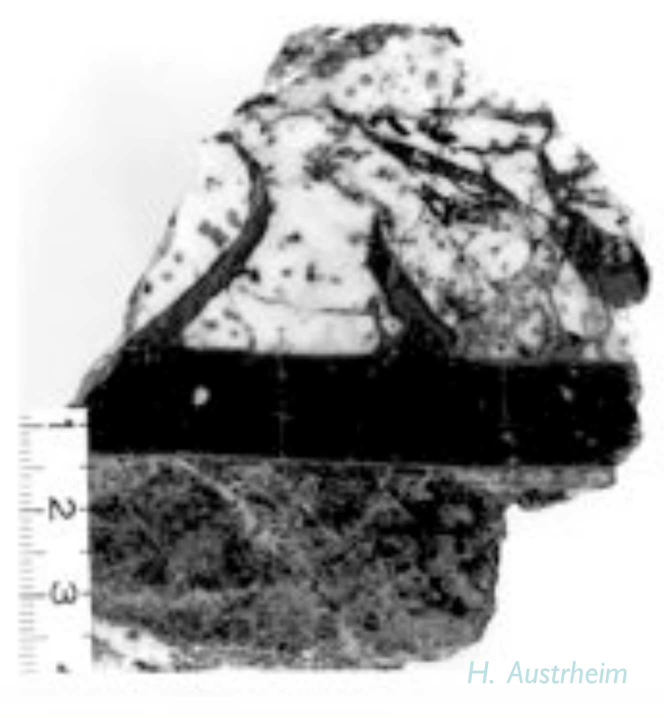
Reading the record of ancient earthquakes at three levels in the crust:

Insights from greenschist-, amphibolite- and eclogite-facies pseudotachylytes



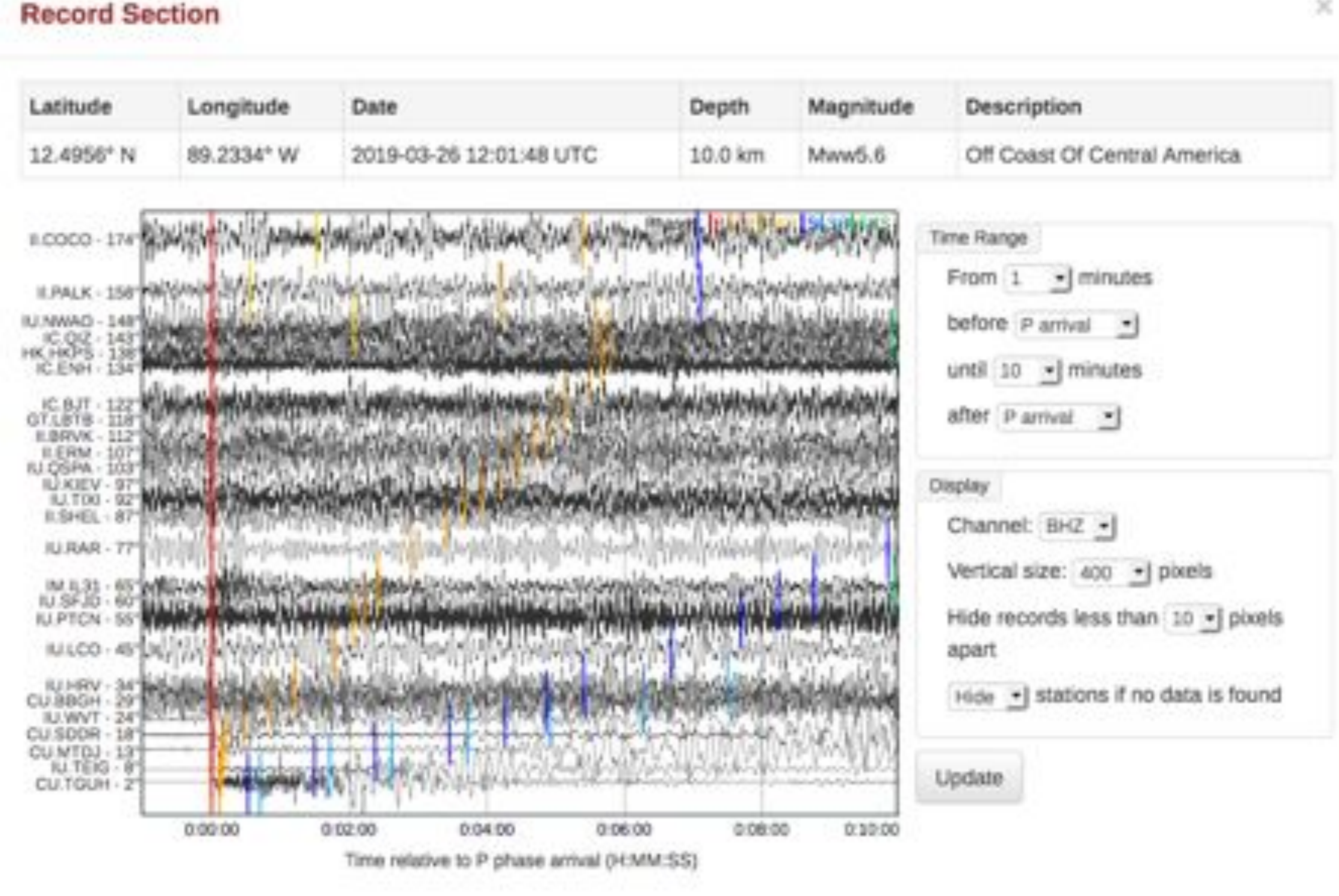
H. Austrheim

Marcia Bjornerud
Lawrence University
Appleton, Wisconsin

Unlike most geologic phenomena, earthquakes occur on human timescales, but seeing what happens at their source is difficult

Amatrice, Italy • 24 August 2016

Much can be inferred about earthquake sources from seismic records…



Record Section

Latitude	Longitude	Date	Depth	Magnitude	Description
12.4956° N	89.2334° W	2019-03-26 12:01:48 UTC	10.0 km	Mww5.6	Off Coast Of Central America

Time Range

From 1 minutes

before P arrival

until 10 minutes

after P arrival

Display

Channel: BHZ

Vertical size: 400 pixels

Hide records less than 10 pixels apart

Hide stations if no data is found

M 5.6 - 110km S of La Libertad, El Salvador

2019-03-26 12:01:48 (UTC) | 12.496°N 89.233°W | 10.0 km depth

Interactive Map

Contributed by US [1]

Regional Information

Contributed by US [1]

Felt Report - Tell Us!

0 0 0 0 1 0

Responses

Contribute to citizen science. Please tell us about your experience.

Citizen Scientist Contributions

Did You Feel It? VII

Community Internet Intensity Map

Contributed by US [1]

ShakeMap III

Estimated Intensity Map

Contributed by US [1]

PAGER GREEN

Estimated Economic Losses

Estimated Fatalities

Contributed by US [1]

Origin

Review Status

REVIEWED

Magnitude

5.6 mww

Depth

10.0 km

Time

2019-03-26 12:01:48 UTC

Contributed by US [1]

Moment Tensor

Fault Plane Solution

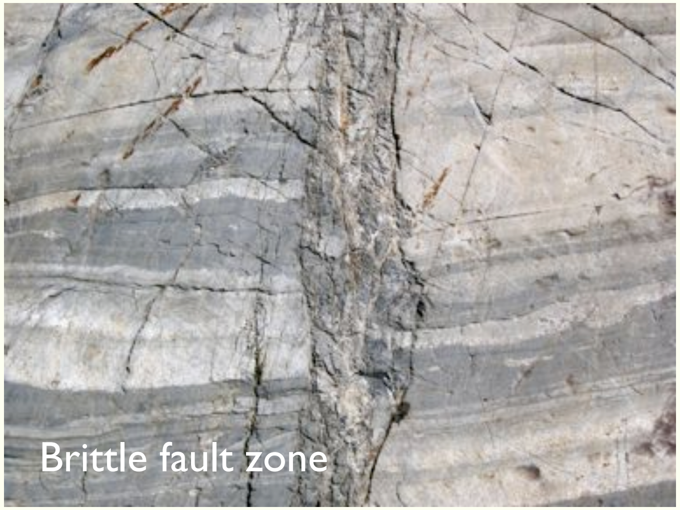
Contributed by US [1]

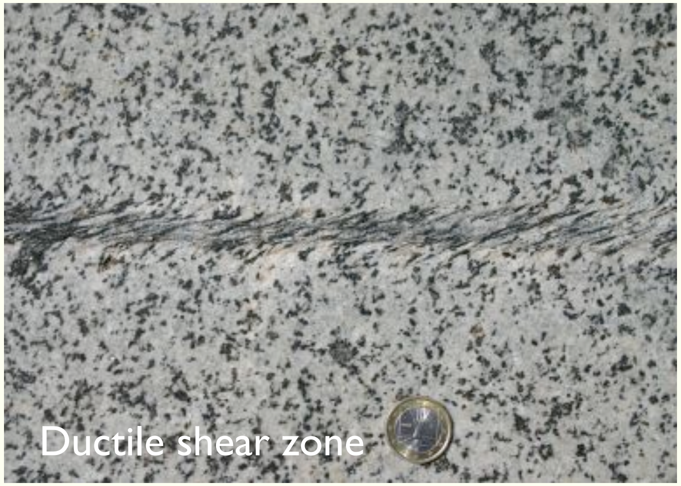
…but direct observations of deformation mechanisms in rocks and the coseismic behavior of fluids at the hypocenter are not possible in real time

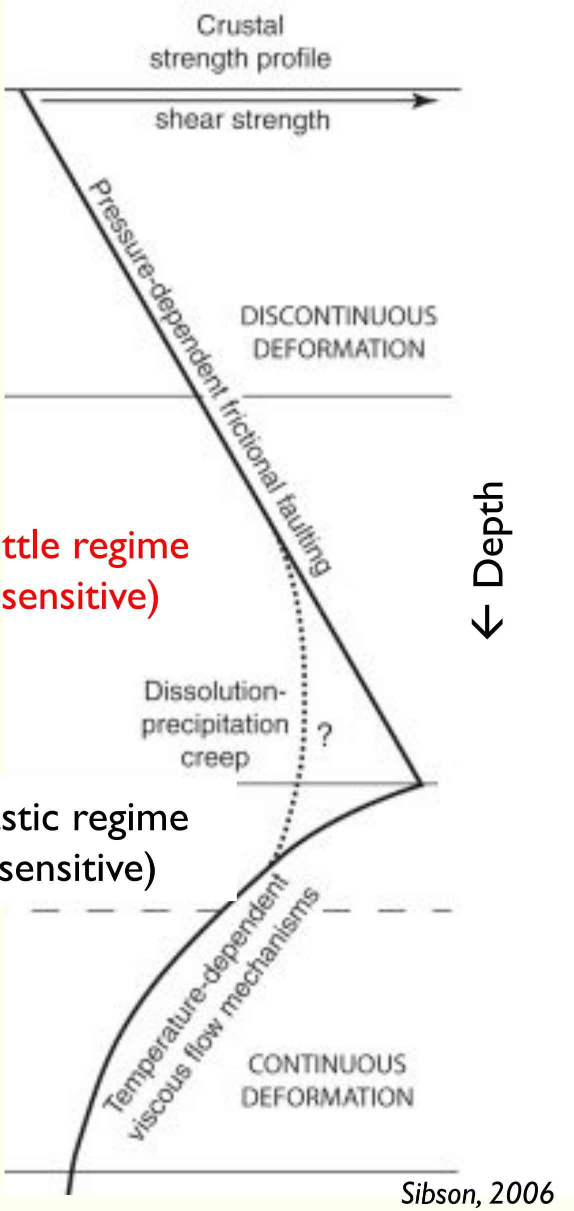
Criteria for seismic fault rupture (slip rates of m/sec)

1) Rocks must be strong -- i.e., able to store stress

Most earthquakes in continental crust nucleate above ~20 km depth – in the brittle regime


Brittle fault zone


Ductile shear zone



Brittle regime (P-sensitive)

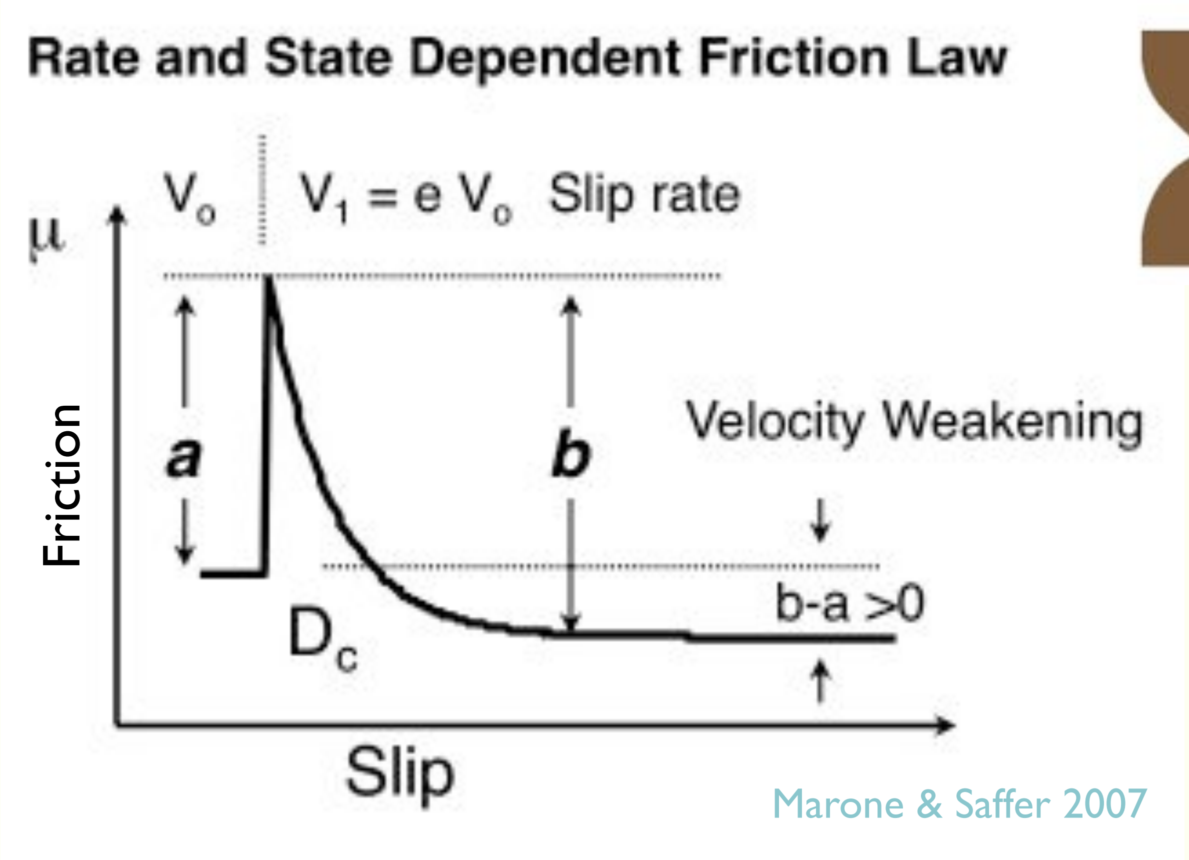
Plastic regime (T-sensitive)

Sibson, 2006

Criteria for seismic fault rupture (slip rates of m/sec)

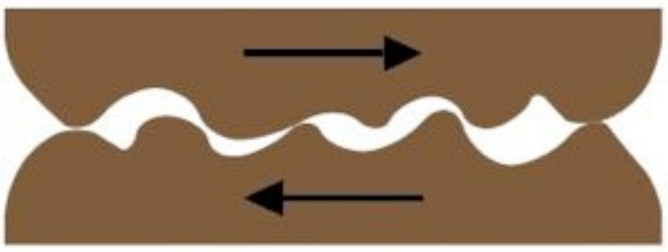
1) Rocks must be strong -- i.e., able to store stress

2) Once slip begins, surface must undergo velocity weakening



Rate and State Dependent Friction Law

Marone & Saffer 2007

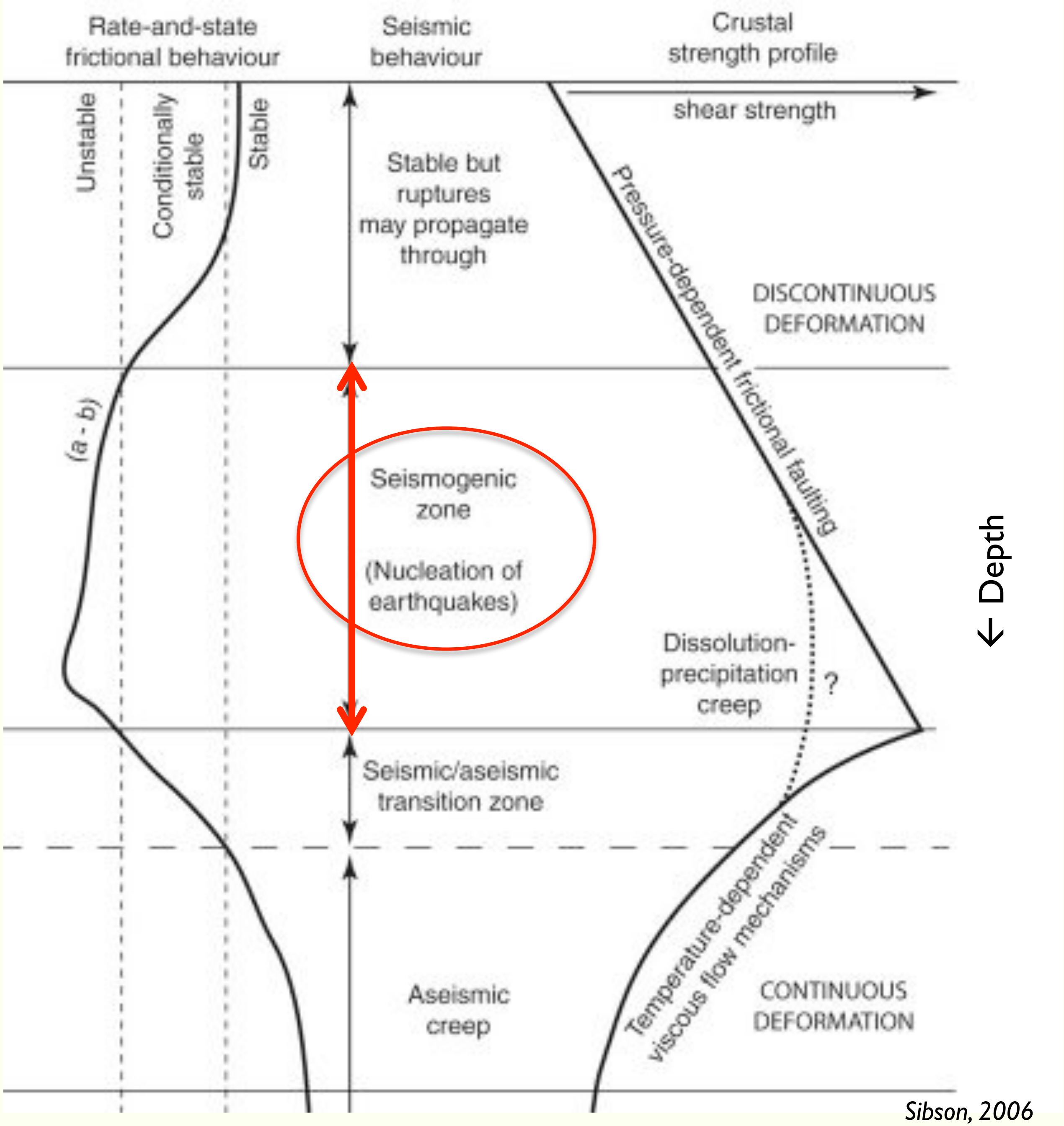


a = instantaneous frictional strengthening as slip begins (asperities collide)

b = dynamic weakening as slip continues

Unstable (seismic) sliding when b-a > 0)

So, most earthquakes in continental crust nucleate between about 5 and 20 km depth – where strong crust can undergo *velocity weakening*

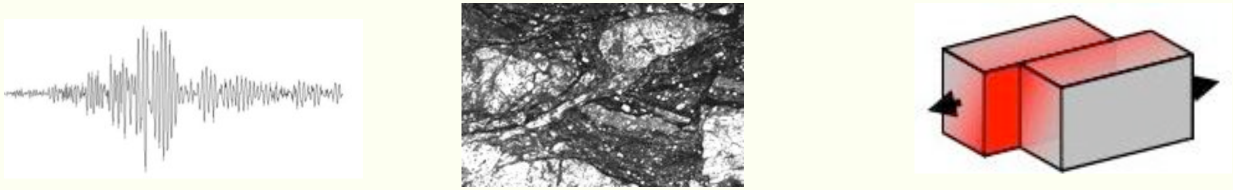


Sibson, 2006

The energy budget of an earthquake

$$W \quad = \quad E \quad + \quad U \quad + \quad Q$$

Work of faulting = Seismic energy radiated + Surface energy of gouge formation + Heat evolved



$E < 10\%$ and $U < 1\%$ of total work done in an earthquake

So, $Q > \sim 0.9\,W$

Therefore, we should see abundant evidence in exhumed fault zones of frictional heating

How is frictional heat consumed in a fault zone?

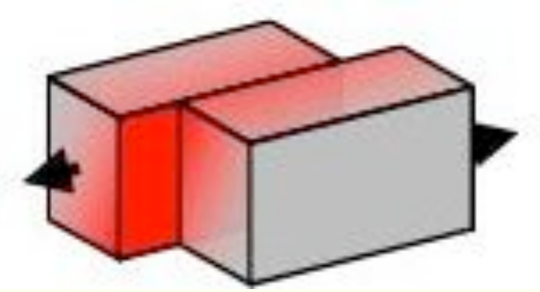
1. **By heating fluids** in the fault zone, leading to **thermal pressurization** (owing to large coefficient of thermal expansion of aqueous fluids)

2. **By heating rock**, sometimes to the point of melting:

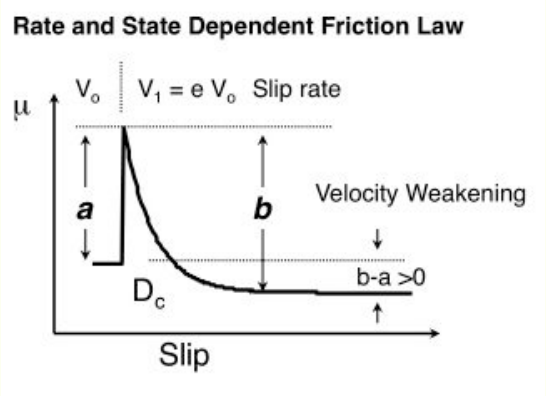
$$Q \text{ (per unit area)} = \tau_f \, D = t \, \rho \, (c\Delta T + \Delta h_{fus} \, (1 - \Phi))$$

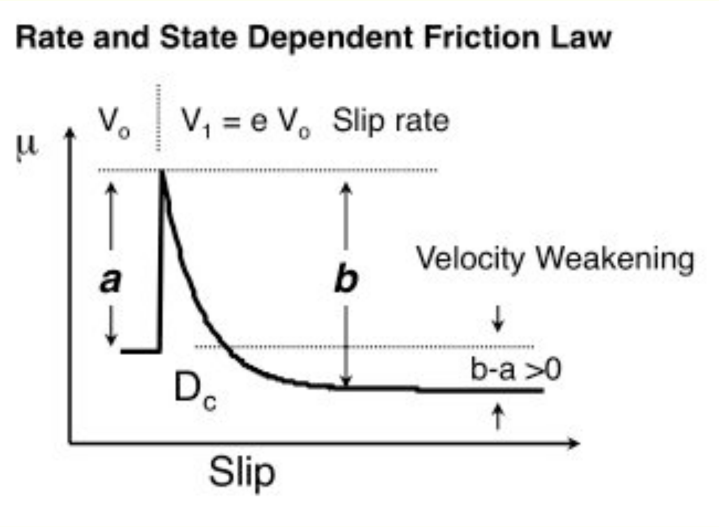
τ_f = shear resistance; D= seismic displacement; t = thickness of melt layer
ρ = rock density; c = specific heat; ΔT = temperature rise; Δh_{fus}= heat of fusion; Φ= fraction unmelted

Very thin work zone (small t) favors melting



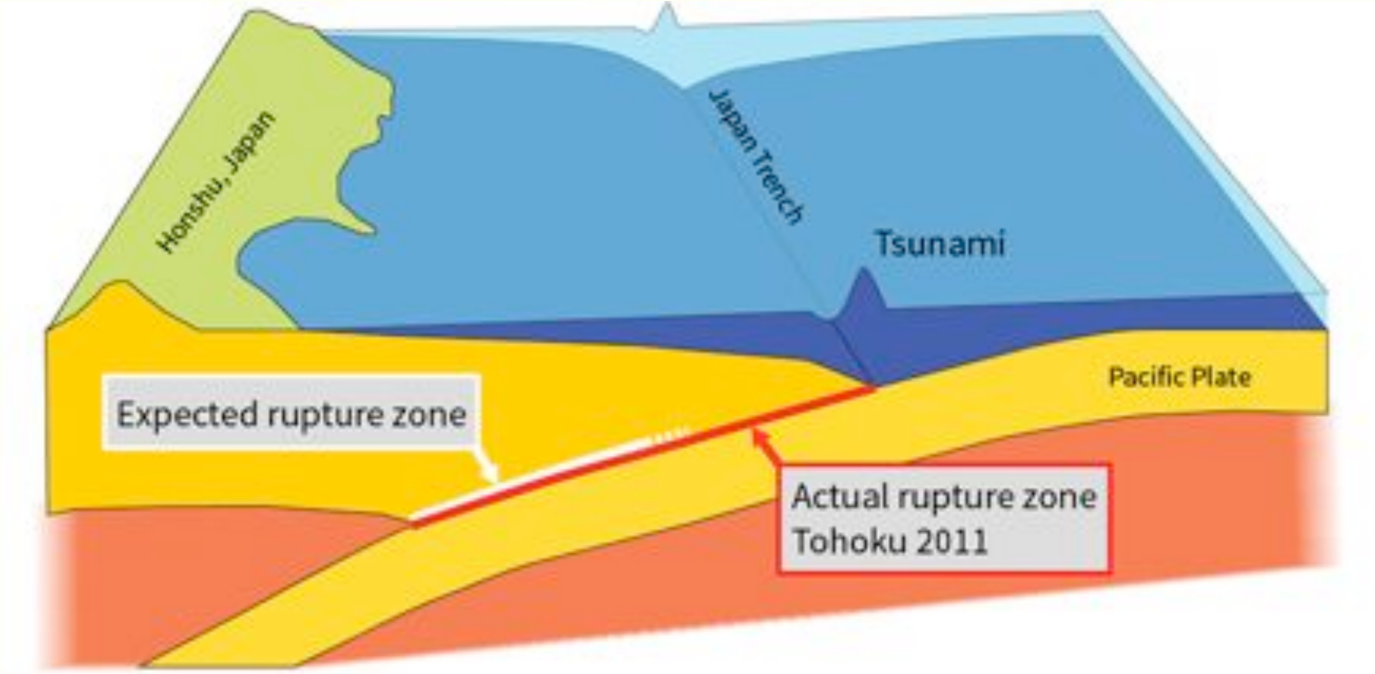
Thermal pressurization, flash heating and melt generation are potential mechanisms of dynamic weakening





Underestimation of potential for dynamic weakening at shallow depths was the reason the magnitude of the 2011 Tohoku earthquake was a surprise

→ *Important to understand co-seismic fluid behavior and conditions under which different types of velocity weakening happen*



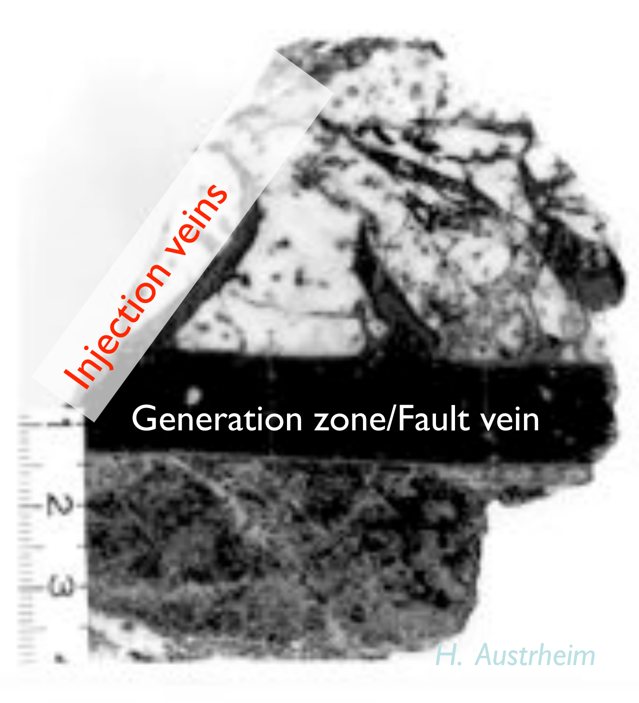
How can we recognize the rock record of ancient earthquakes?

Not all fault rocks formed in seismic events

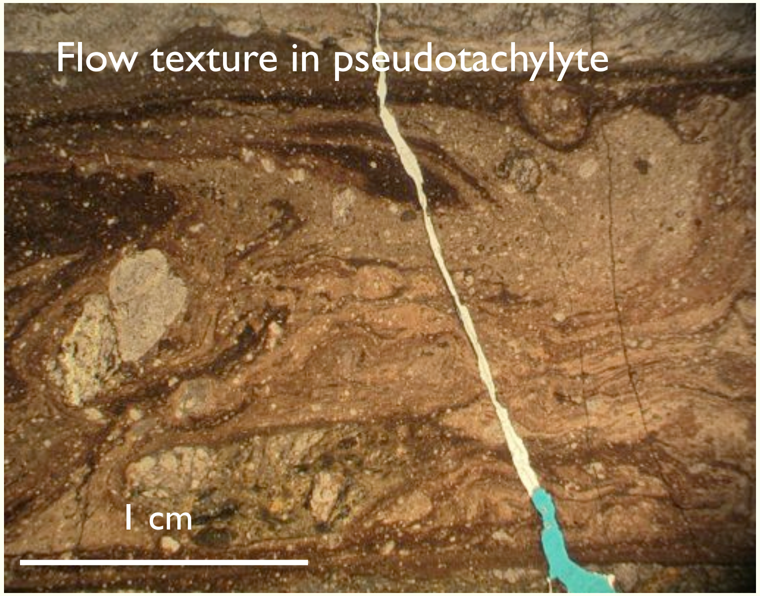
Pseudotachylyte has been considered the only unambiguous record of seismic slip on ancient faults.

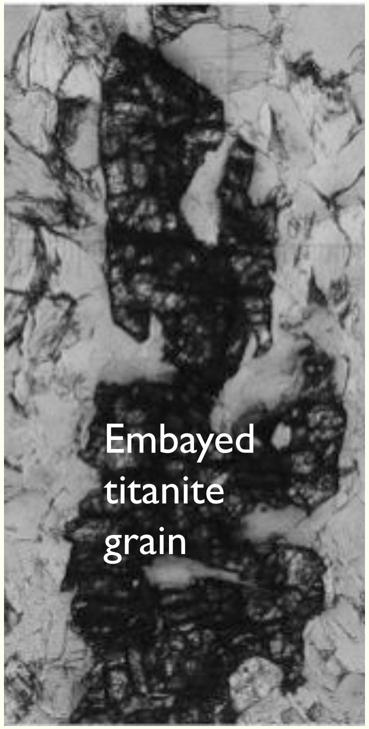
Criteria for recognition include:

Fault vein/injection vein geometry • Flow textures
Microlites with quench textures • Geochemistry matching host rock;
Embayed grains/margins • Preferential survival of large or refractory grains



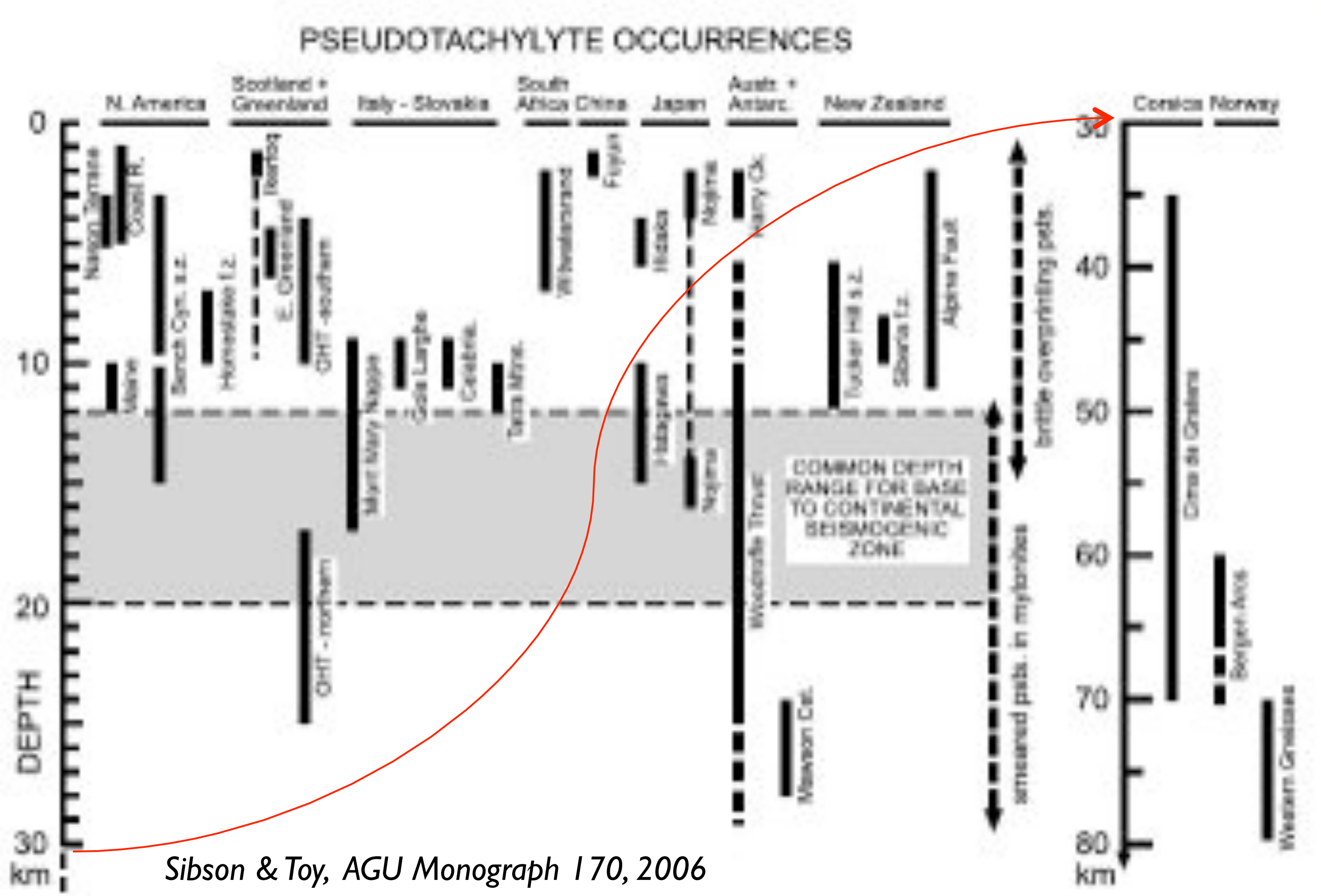
H. Austrheim





0.5 mm

Plane light



Sibson & Toy, AGU Monograph 170, 2006

Structural geologists have known about pseudotachylyte for >20 years, and it has been documented in fault zones representing a wide range of depths but is still rather rarely found.

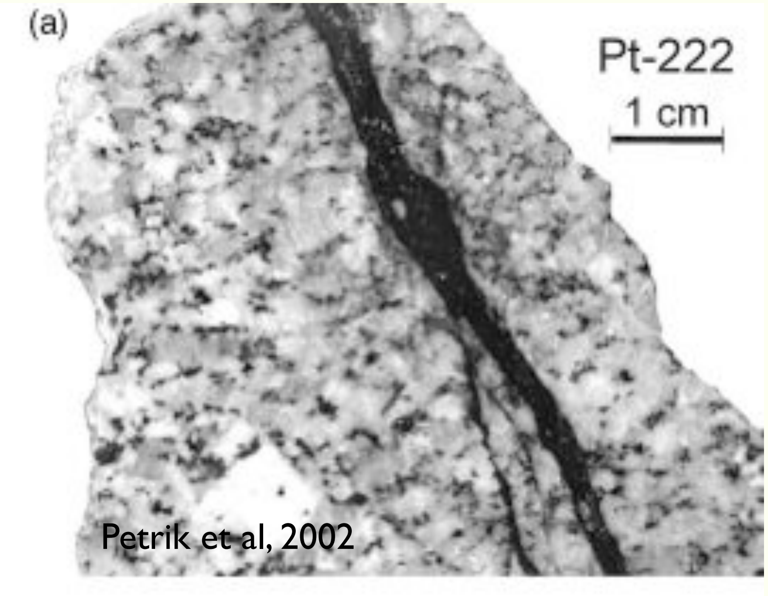
Given the number of large earthquakes that have happened over geologic time, this is strange!

Preservation potential is likely only part of the answer

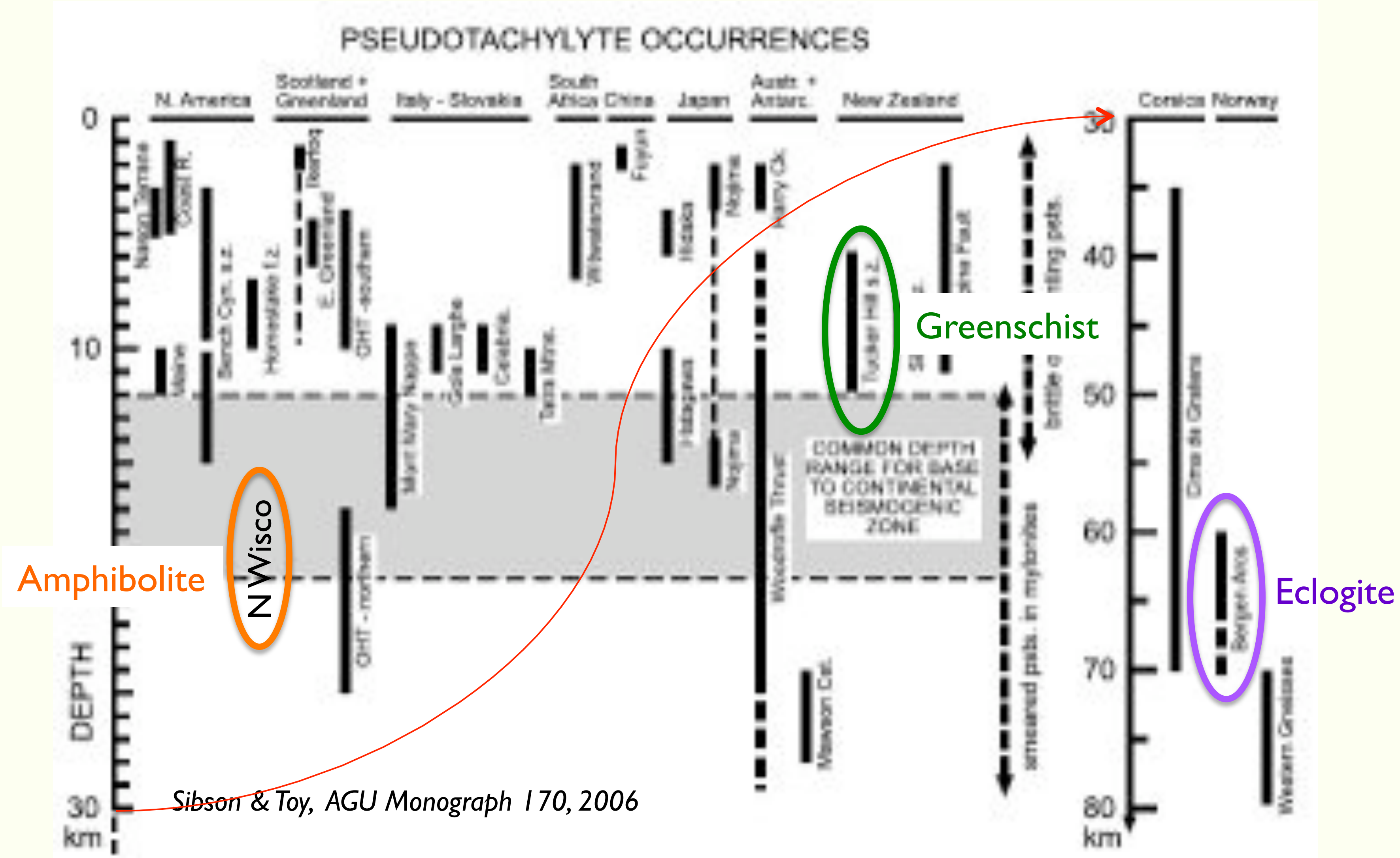
Conventional wisdom has been that **Melt generation and thermal pressurization are mutually exclusive**

"Thermal pressurization of fault fluids during seismic slip inhibits melt generation…Pseudotachylyte represents **high-stress** (τ>100 MPa) **rupturing** associated with fault initiation or reactivation **in dry, intact** (or metamorphically reconstituted) **crystalline crust**. Its scarcity is accounted for by the progressive infiltration of aqueous fluids into evolving fault zones". (Sibson & Toy, AGU Monograph 170, 2006)

This does seem consistent with many of the classic occurrences, in which thin bands of pseudotachylyte cut through otherwise pristine rock



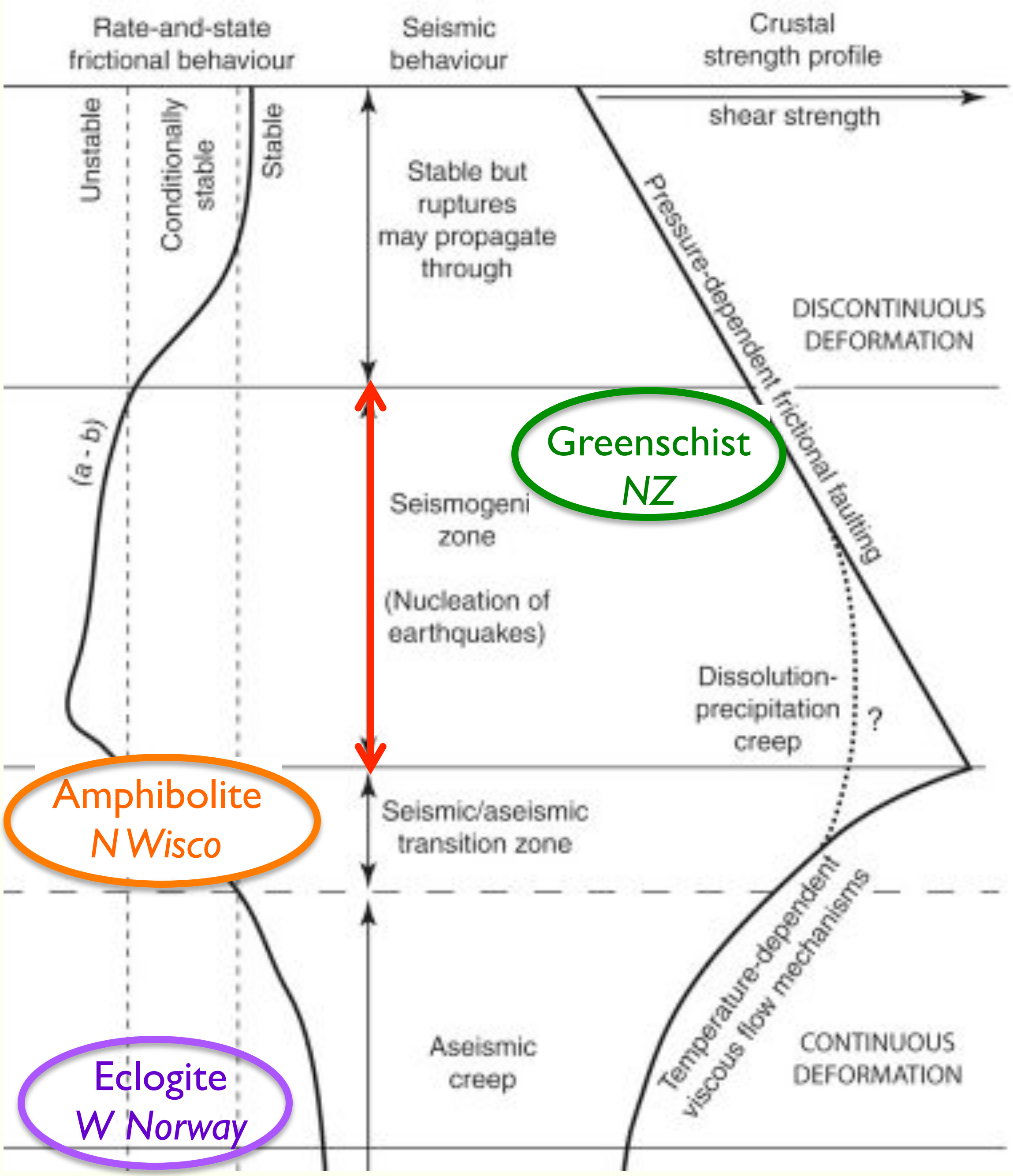
Petrik et al, 2002



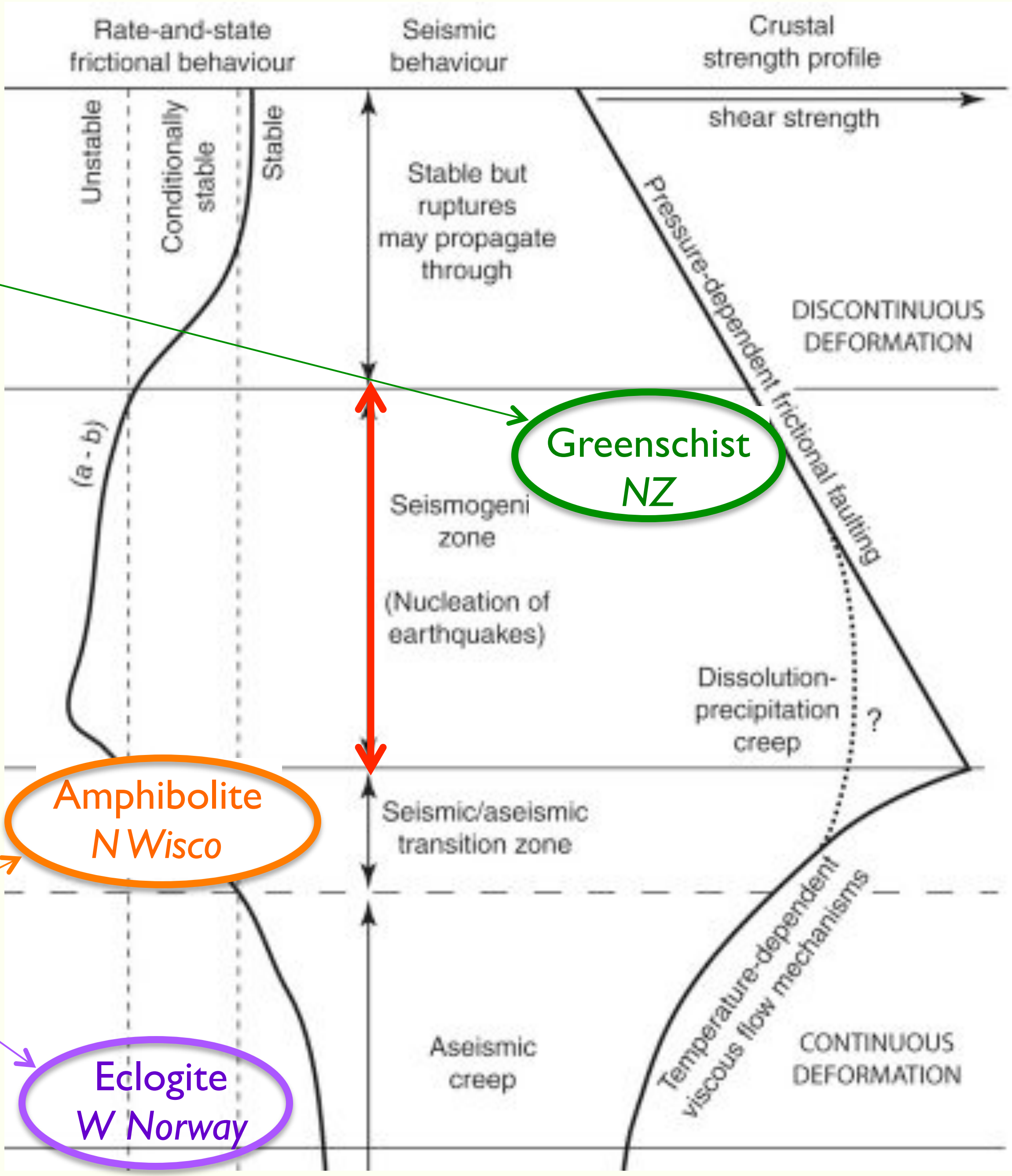
Sibson & Toy, AGU Monograph 170, 2006

But other pseudotachylyte occurrences suggest a more complex relationship between rock mechanics and fluid behavior during earthquakes

Three pseudotachylyte occurrences representing different crustal depths – all violate conventional wisdom

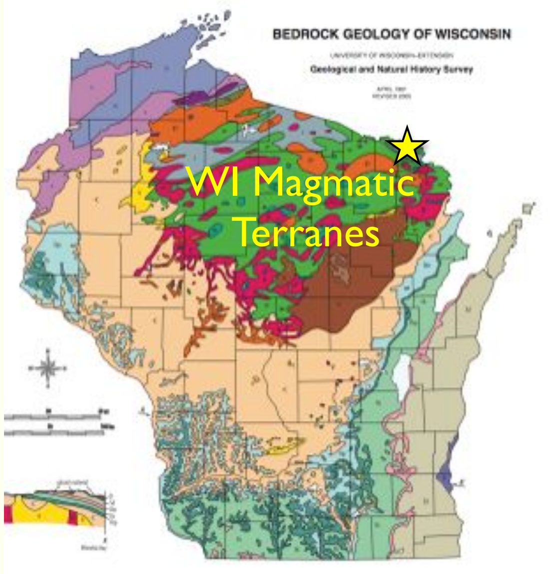


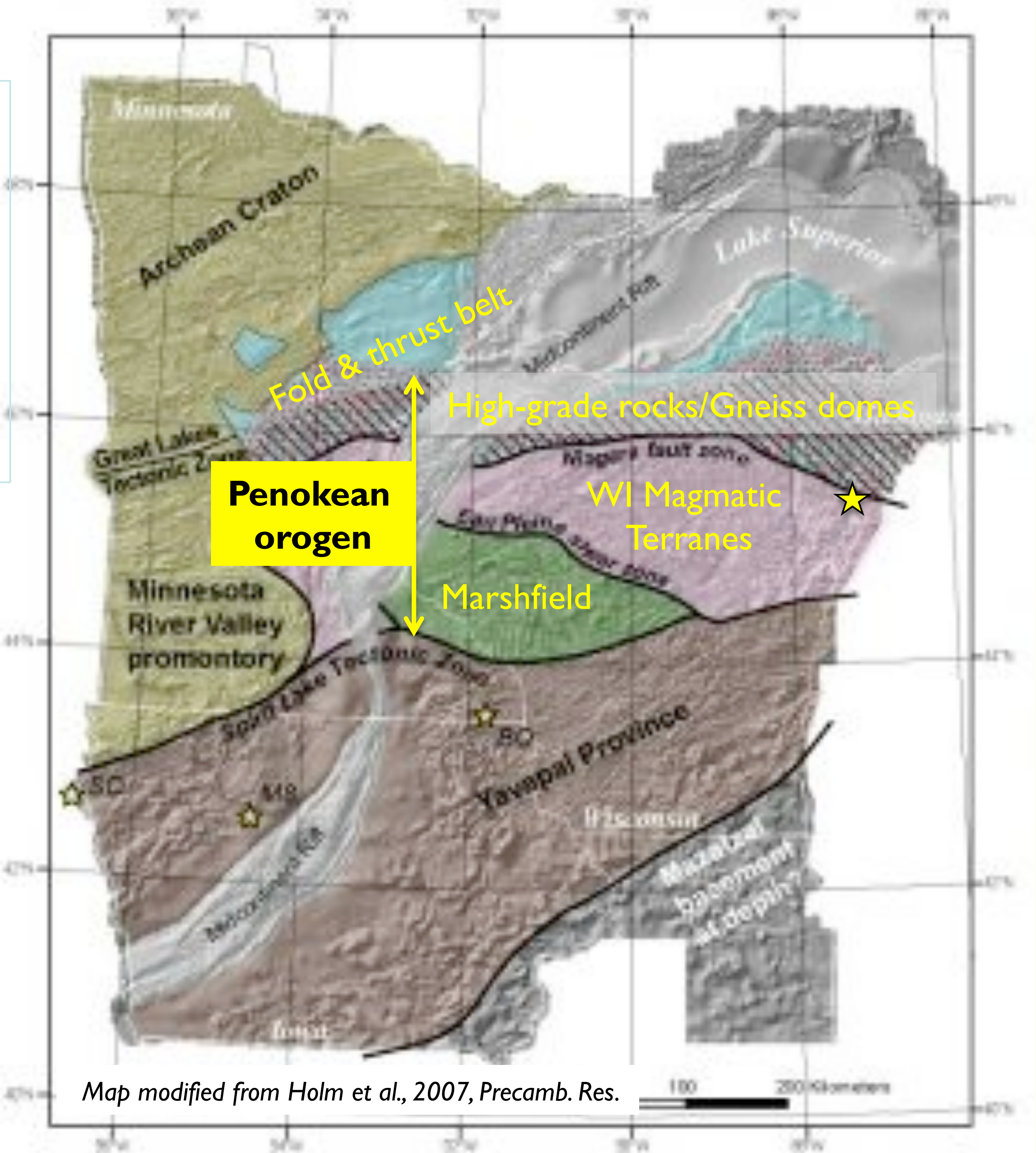
Rocks were full of water – thermal pressurization should preclude melting.
Why is pseudotachylyte here?



Rocks below - or far below - seismogenic zone.
Why are earthquakes happening here?

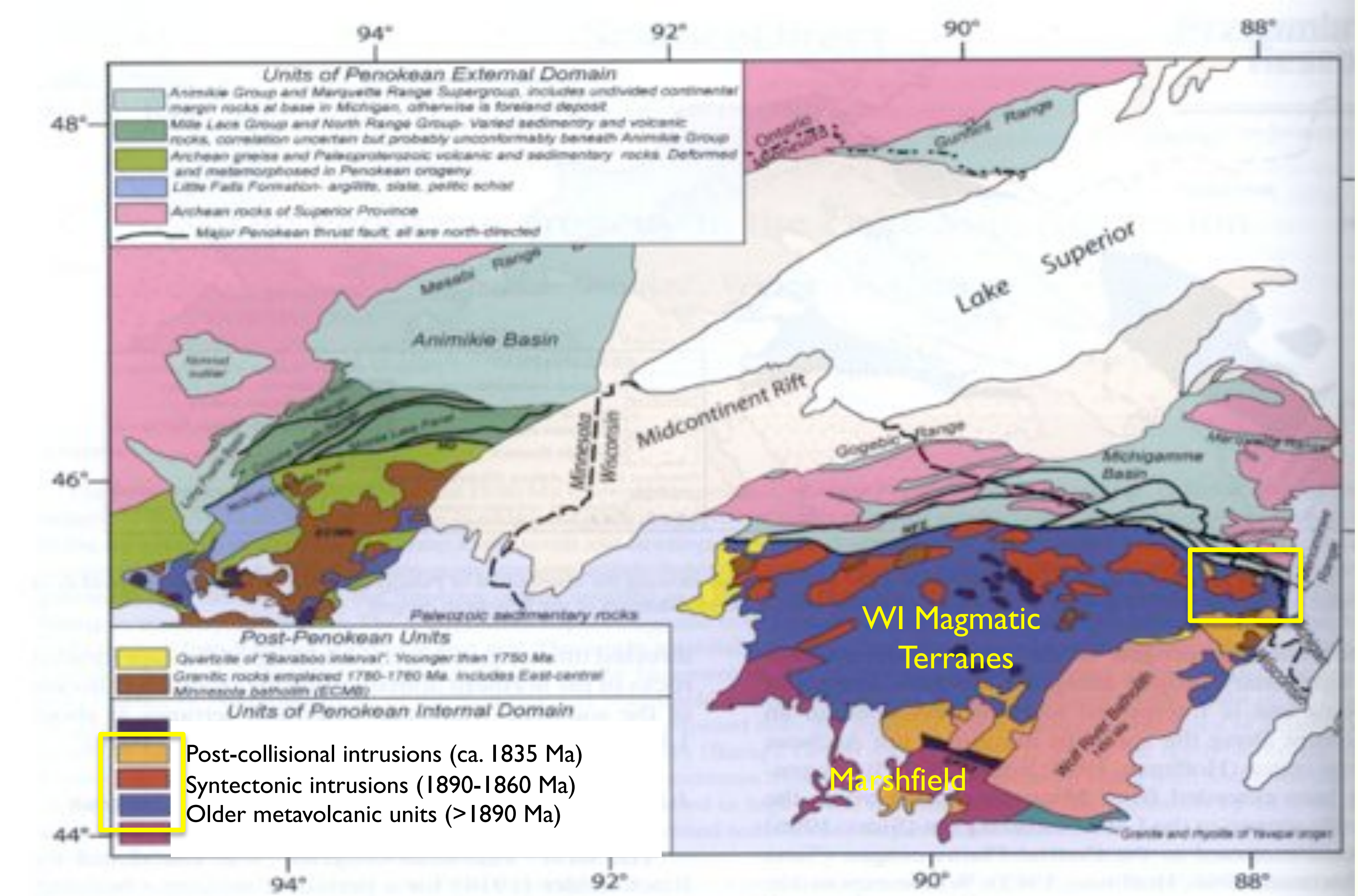
Case study I:
Amphibolite-facies pseudotachylytes and mylonites along the Twelve-Foot Falls Shear Zone, NE Wisconsin





Map modified from Holm et al., 2007, Precamb. Res.

A closer look at the Wisconsin Magmatic Terranes

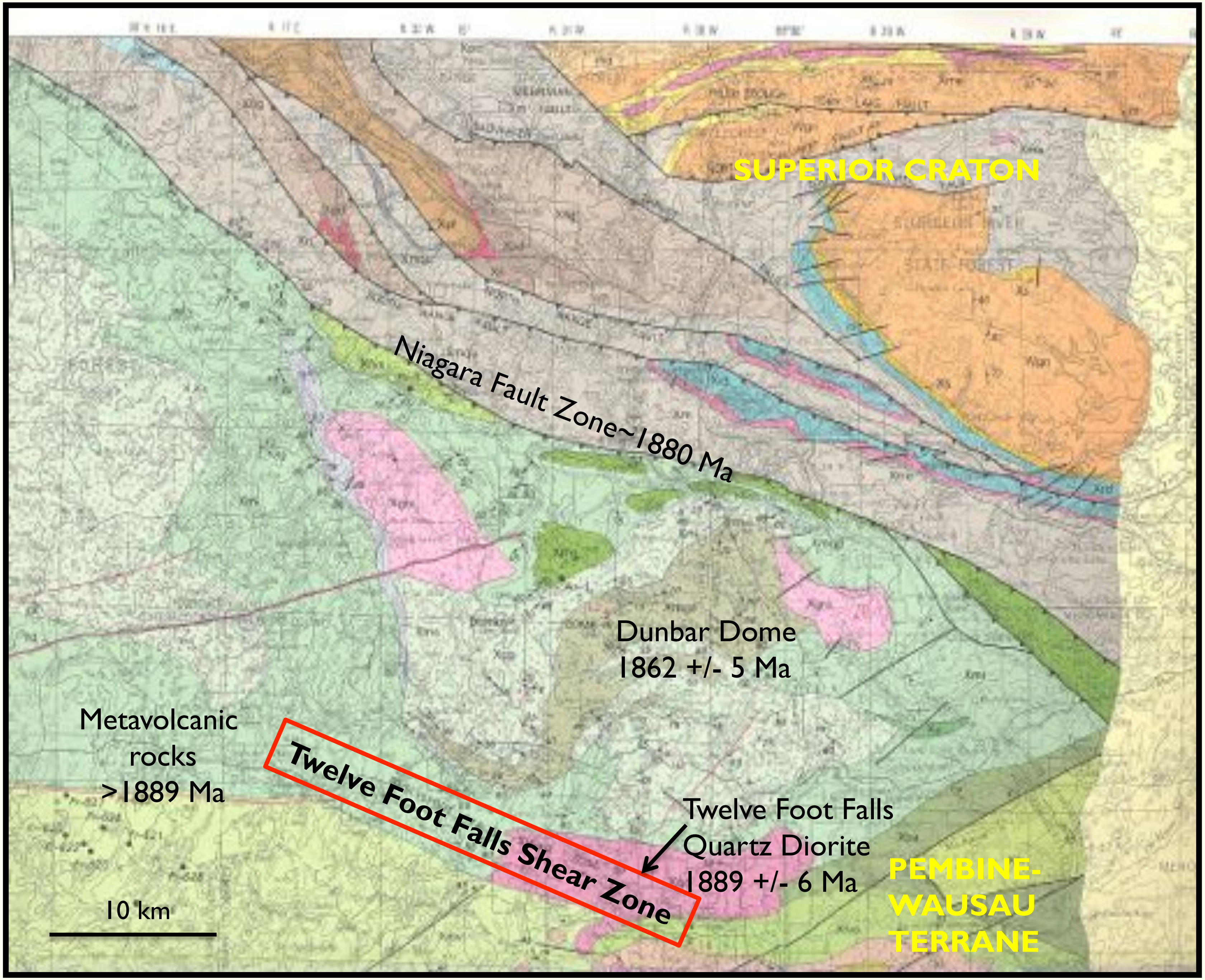


Post-collisional intrusions (ca. 1835 Ma)
Syntectonic intrusions (1890-1860 Ma)
Older metavolcanic units (>1890 Ma)

WI Magmatic Terranes

Marshfield

From Schulz & Cannon, 2007, Precamb. Res.



SUPERIOR CRATON

Niagara Fault Zone~1880 Ma

Dunbar Dome
1862 +/- 5 Ma

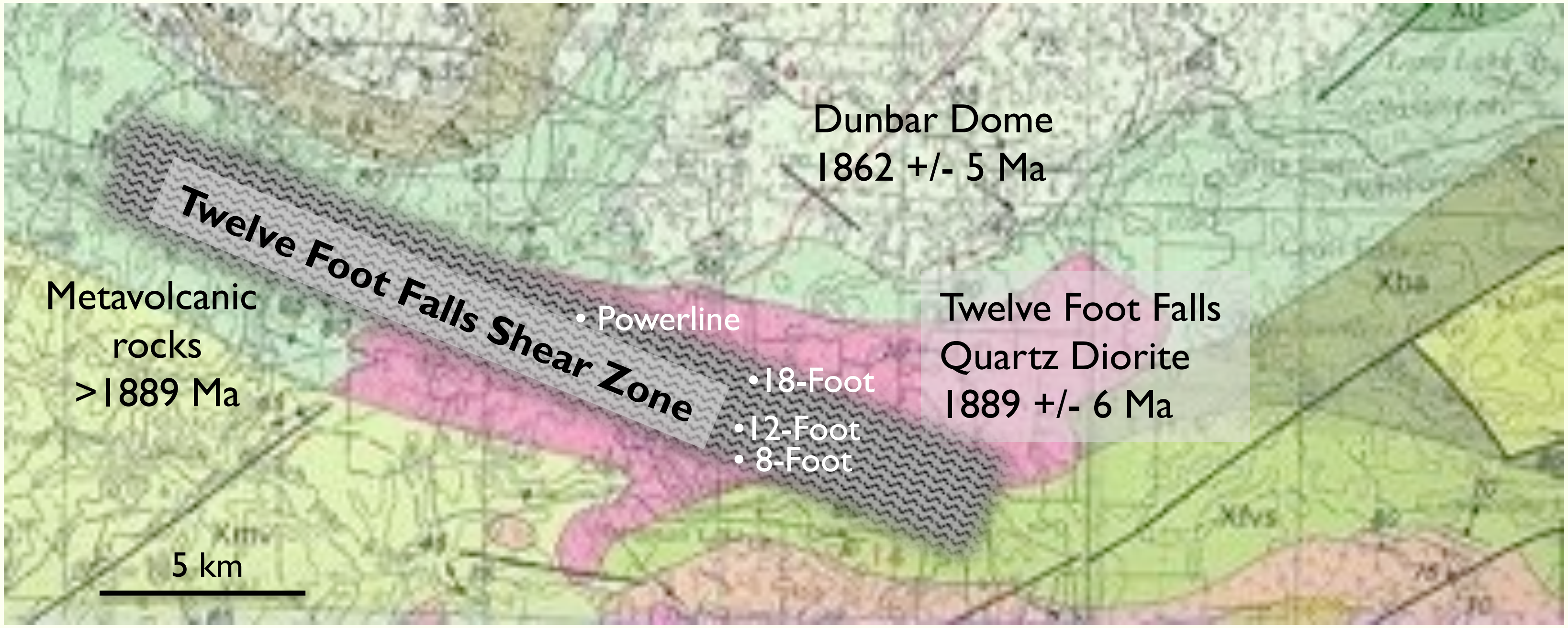
Metavolcanic
rocks
>1889 Ma

Twelve Foot Falls Shear Zone

Twelve Foot Falls
Quartz Diorite
1889 +/- 6 Ma

PEMBINE-
WAUSAU
TERRANE

10 km

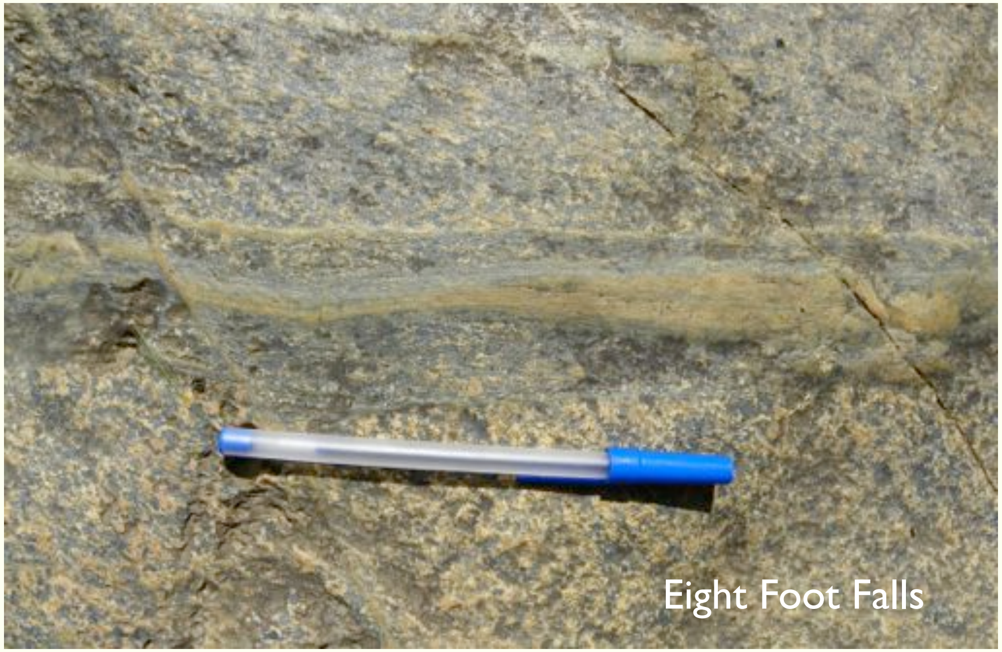


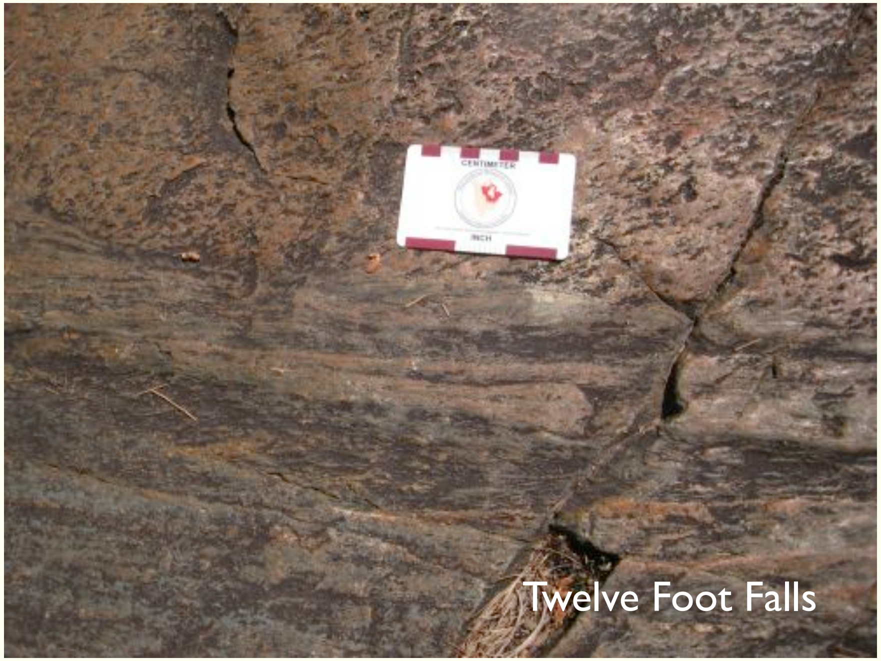

Twelve Foot Falls

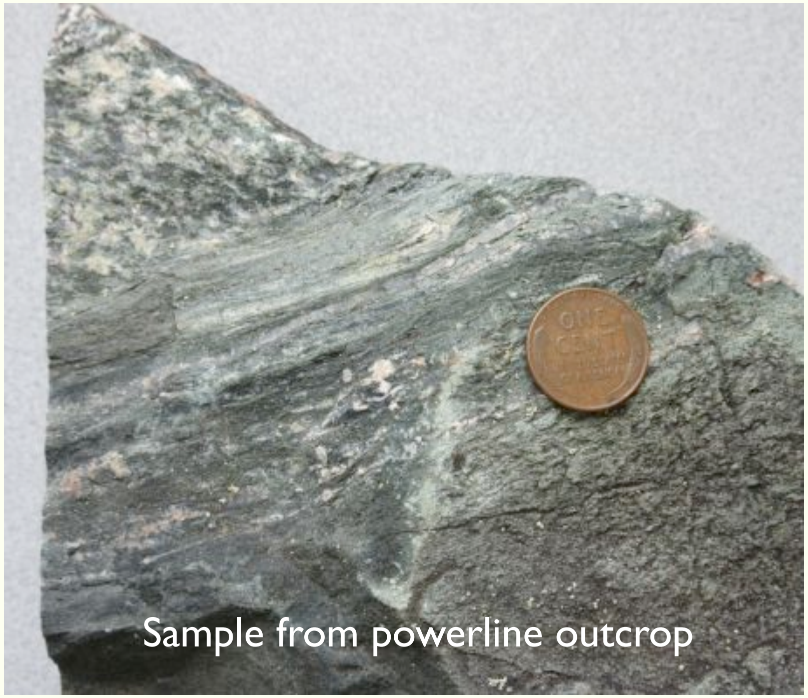

Eight Foot Falls

Mylonites along the 12 Foot Falls SZ

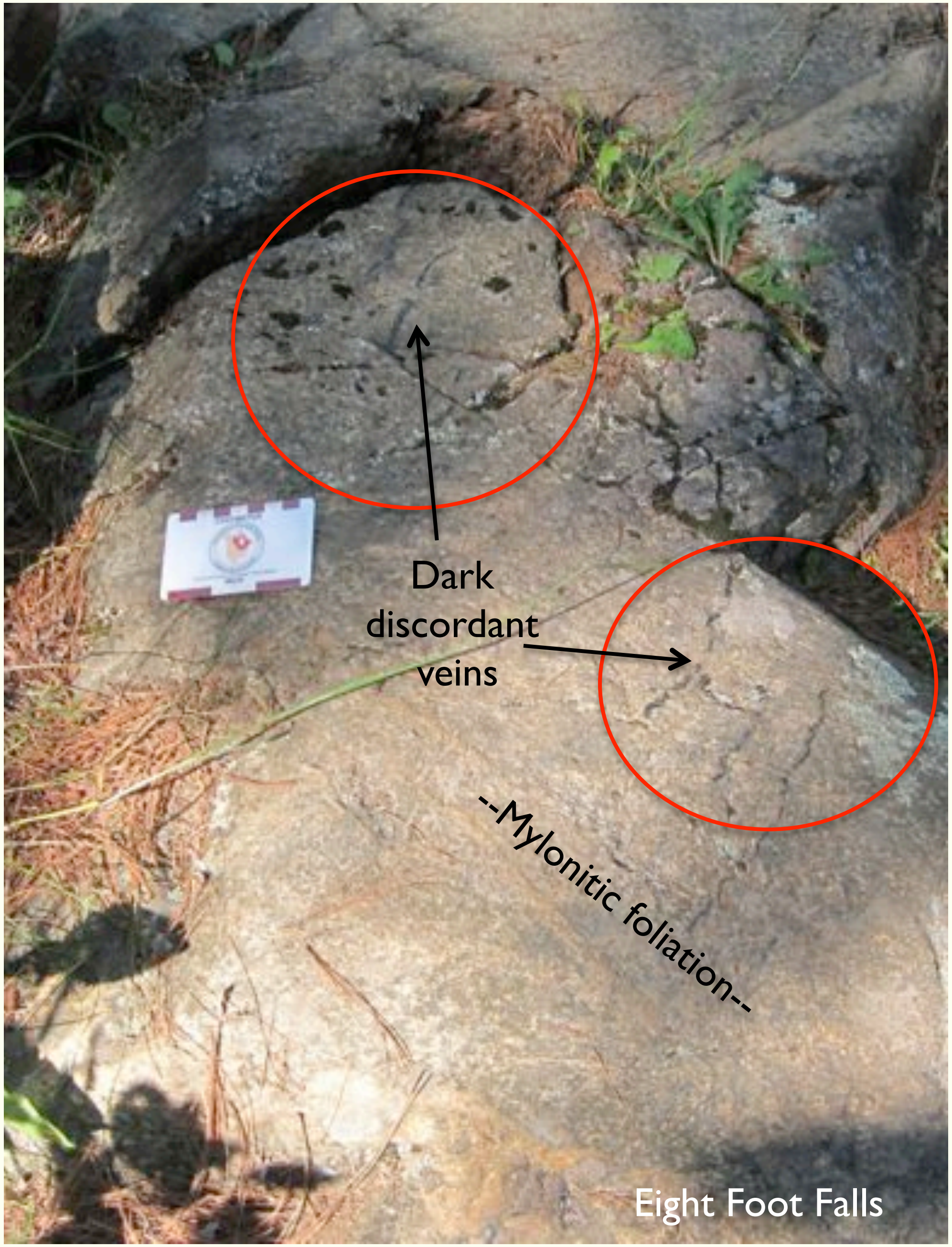
- Mainly parallel to shear zone as a whole and to regional foliation (~N75°W, subvertical)
- 1 cm - 1 m wide
- Characterized by large strain gradients
- Weak down-dip lineation; Sense of shear unclear


Eight Foot Falls

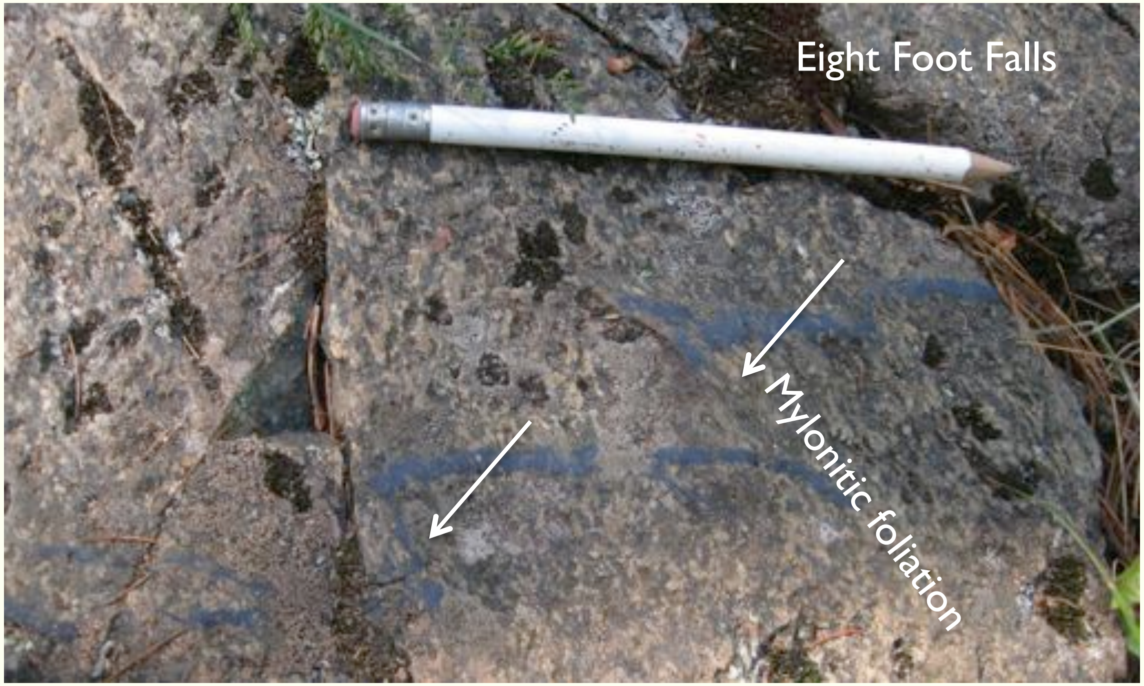

Twelve Foot Falls


Sample from powerline outcrop

In thin section, mylonites are finer grained than surrounding rock, but have same microstructural character – strongly deformed to partly annealed quartz bands and broken/boudinaged hornblende (typically altered to chlorite)

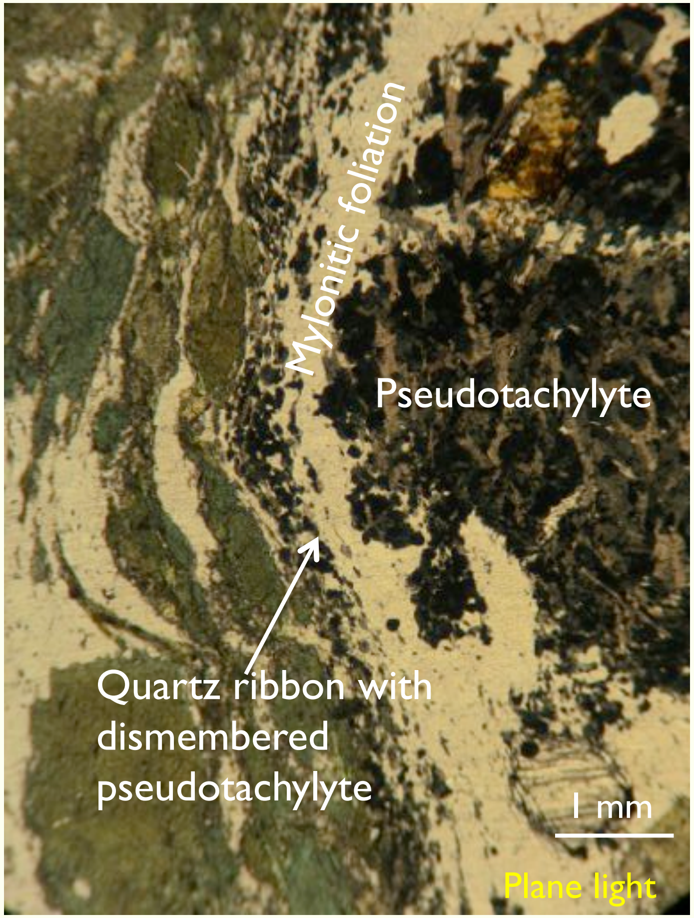


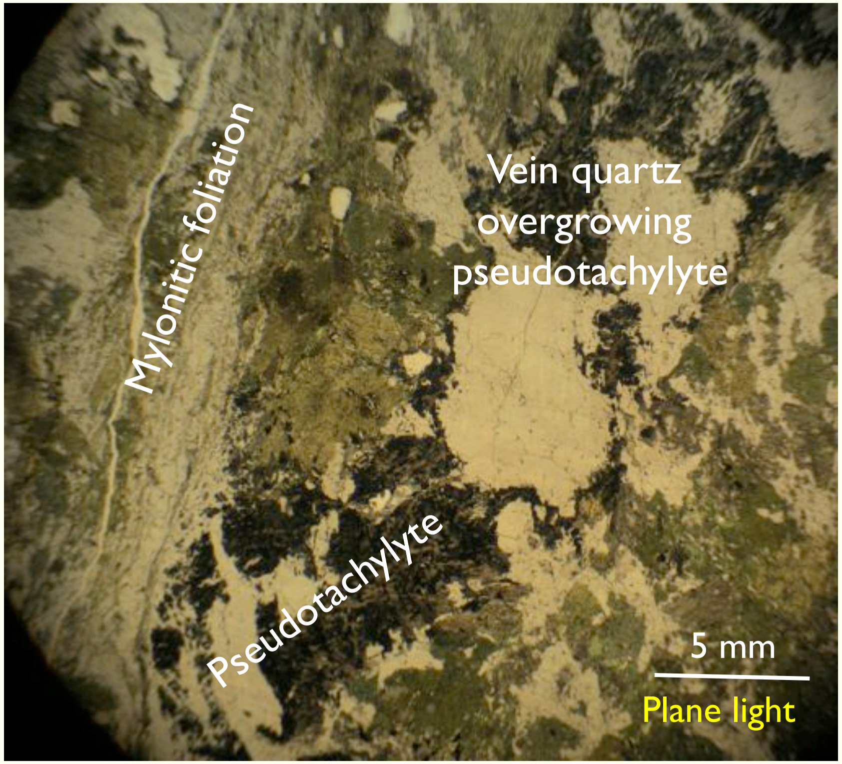
Pseudotachylyte injection veins are transverse to foliation and mylonitic fabric, but foliation planes acted as generation surfaces



In places, the injection veins have themselves been offset along mylonitic foliation

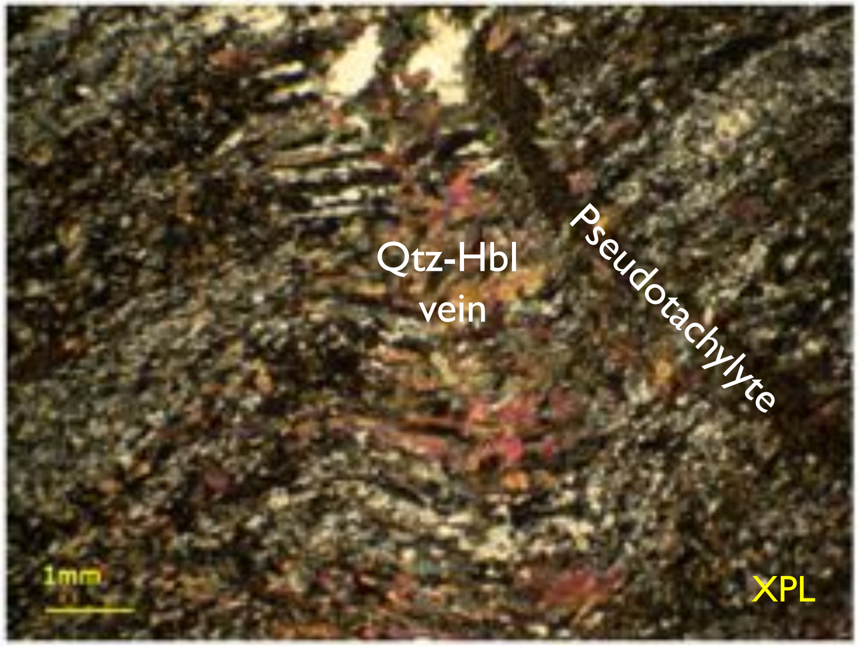
In thin section, mylonite truncates and incorporates pseudotachylyte, and pseudotachylyte is overprinted by metamorphic grain growth





→ Pseudotachylyte and mylonite formed in alternation at peak metamorphic conditions

Fibrous ‘crack-seal’ veins of hornblende and quartz indicate intermittent hydrofracturing and fluid flow at high-temperature conditions



Possible that fluids were pumped into transiently dilatant areas during earthquake rupture

Presence of fluids apparently did not inhibit pseudotachylyte formation – not present along slip surfaces that generated melt?

Perhaps interseismic mylonitic deformation ‘resealed’ fault zone and prevent further fluid infiltration

Mutually cross-cutting relationships between pseudotachylyte and mylonite indicate that deformation occurred at depth of seismic/aseismic transition

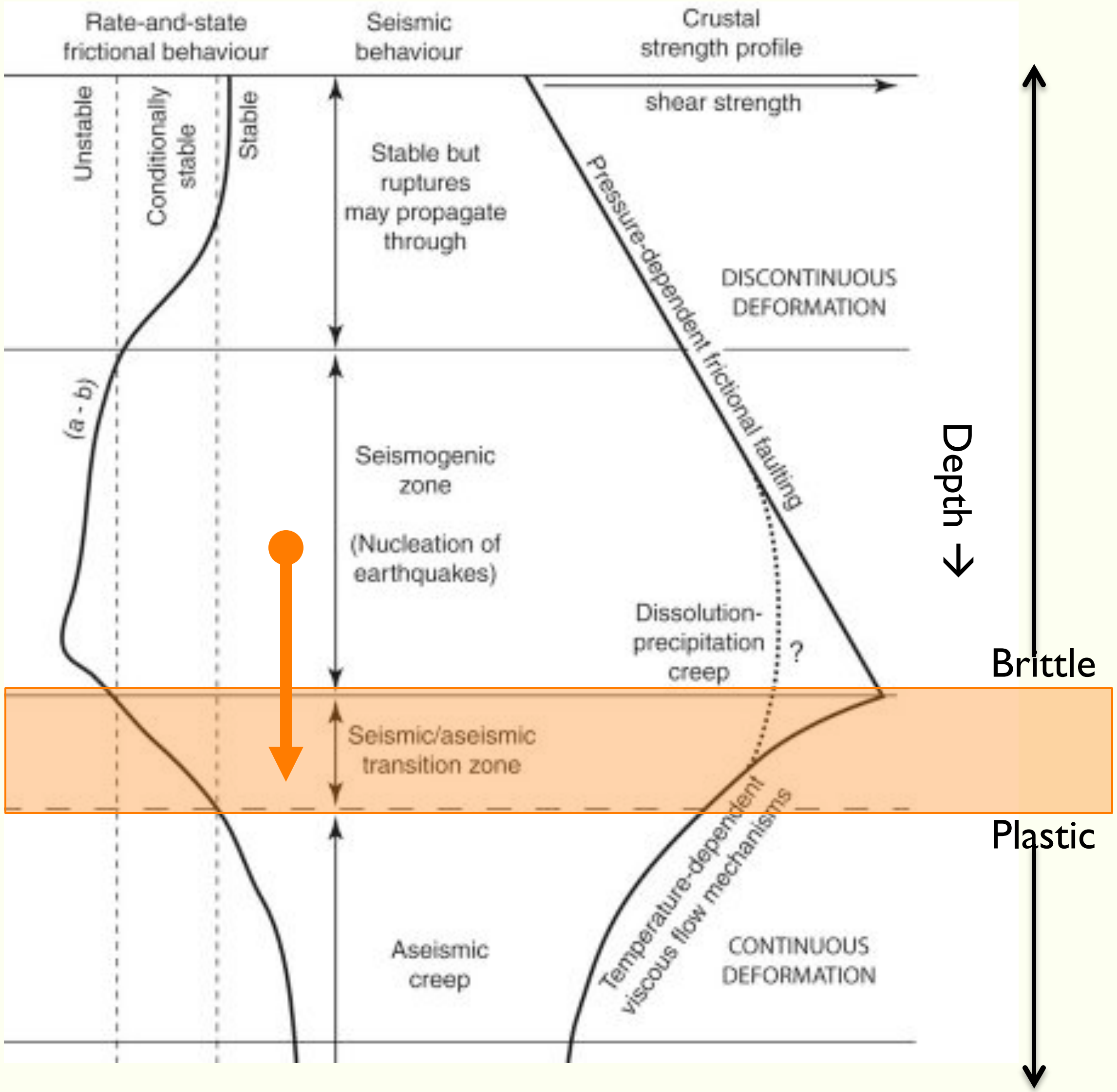
Inferences from the Twelve-Foot Falls pseudotachylytes:

Large earthquake ruptures likely propagated downward into normally aseismic ductile regime (converse of Tohoku case)

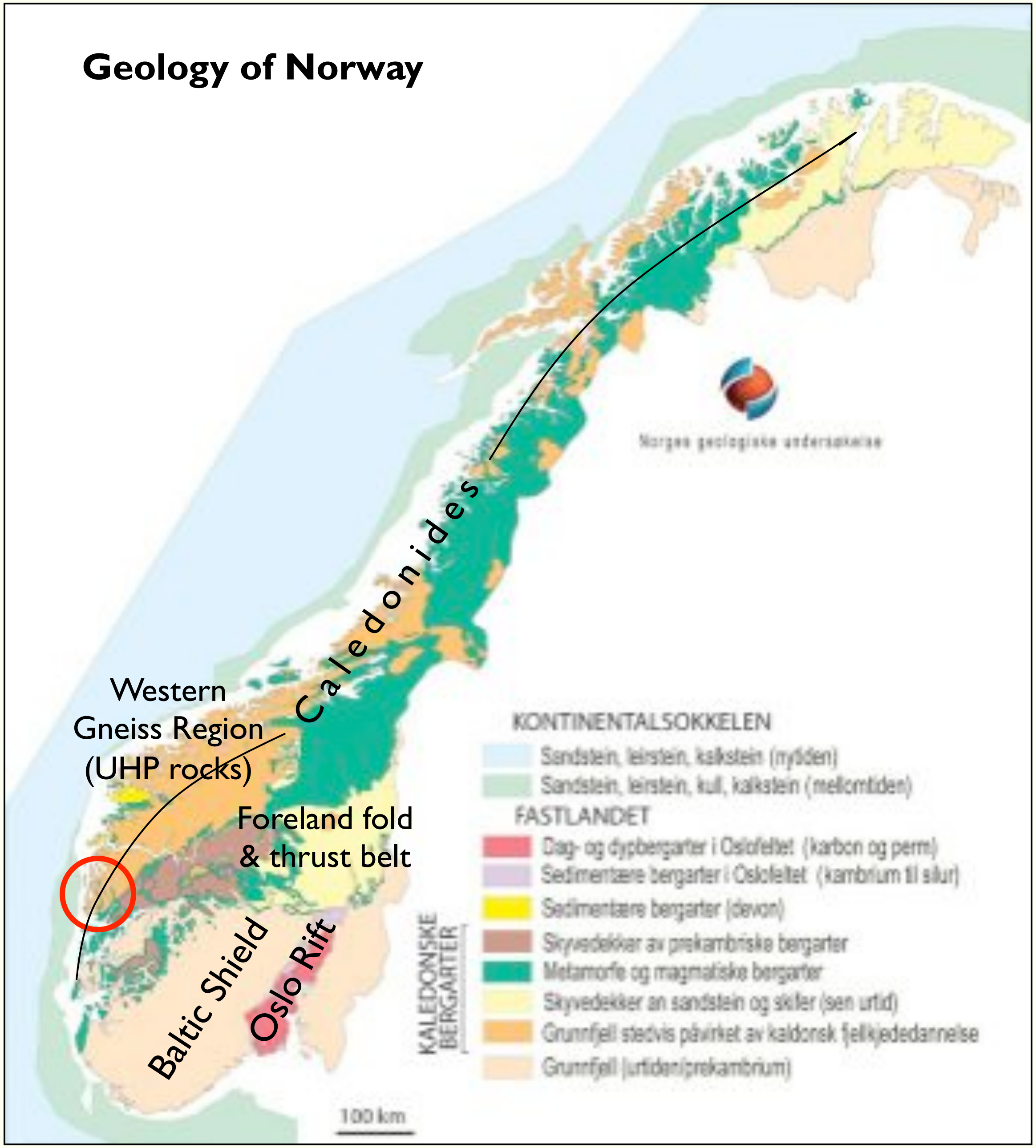
Frictional melting (pseudotachylyte generation) may have been a velocity-weakening mechanism

Fluids were present but not localized on slip planes

Post-seismic plastic deformation may have resealed fault

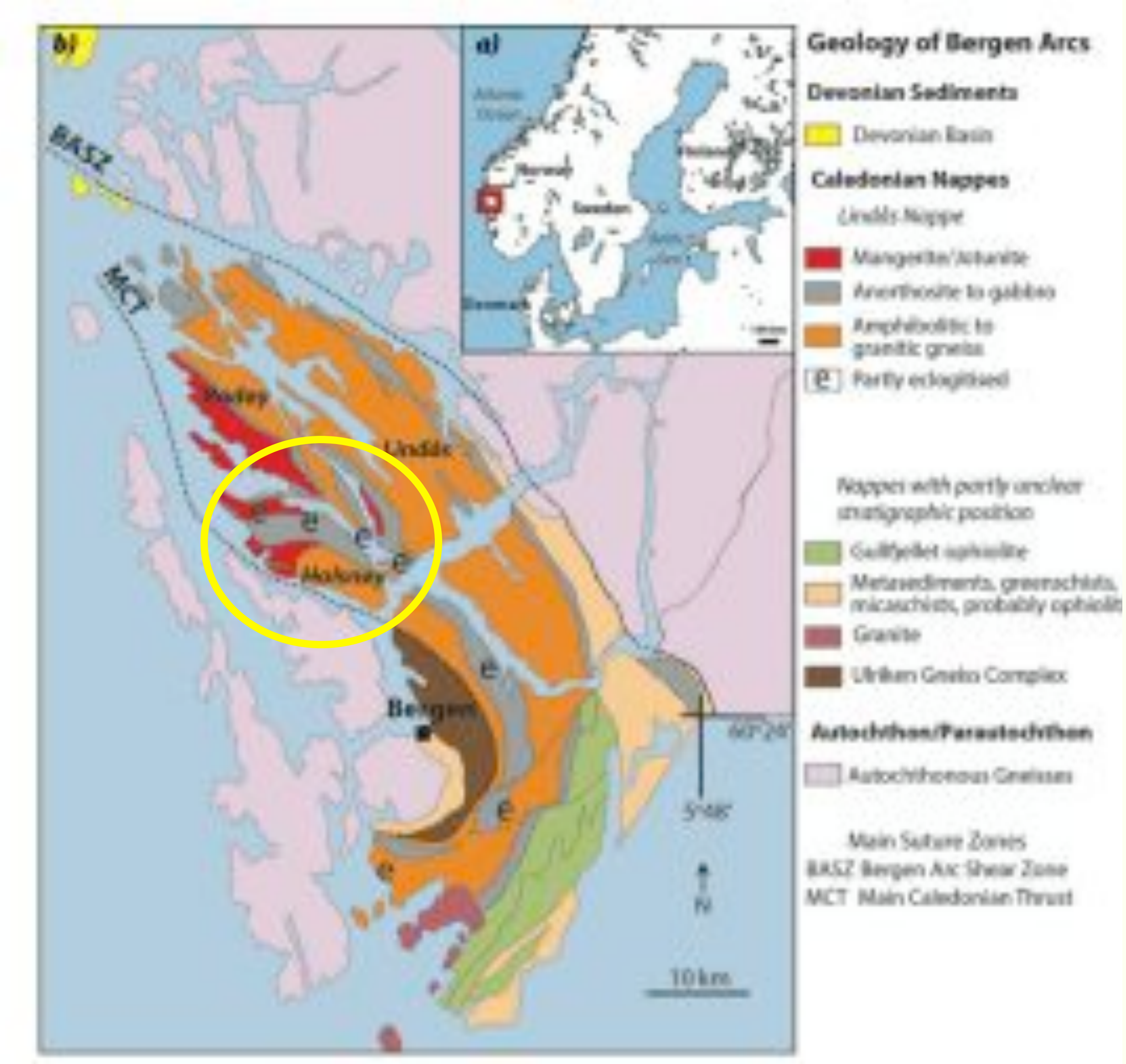


Case study II:
Eclogite-facies
pseudotachylytes in
mafic granulite
gneisses,
Holsnøy, Bergen Arcs,
Norway



Geology of Norway

Bergen ‘arcs’: Two cycles of crustal thickening & metamorphism
“Grenvillian” and Caledonian



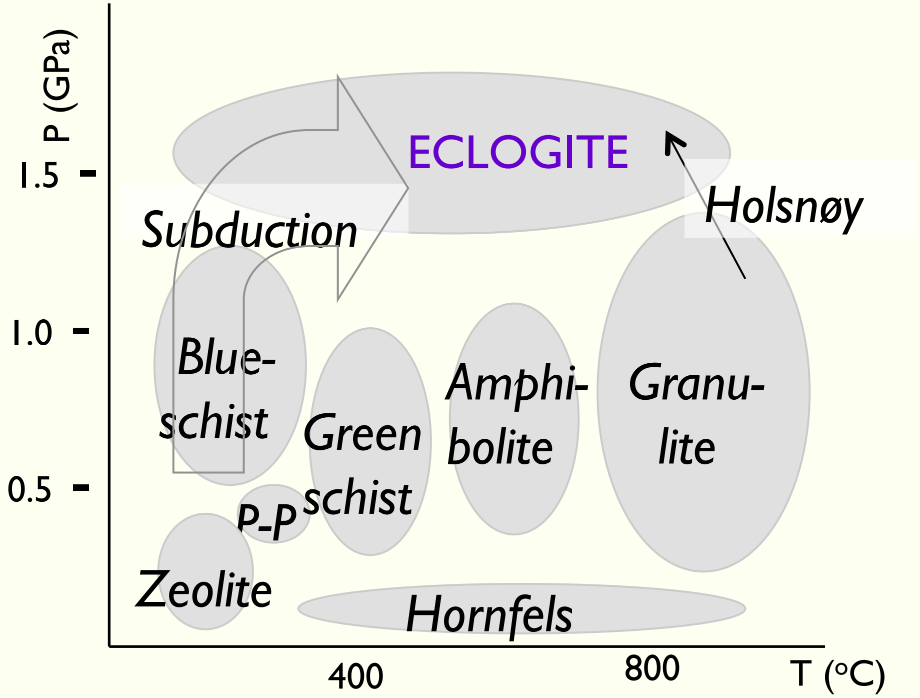
Island of Holsnøy:
Protolith: Anorthosite, gabbro, minor peridotite (layered mafic intrusion?)

Transformed to mafic gneiss at ca. 945 Ma under granulite conditions

Metamorphic history of rocks on Holsnøy

- At ca. 945 Ma, rocks experienced granulite conditions: 800-900°C, 1.0 GPa. [Gt + Cpx + Plag ± Opx]
- The granulite event left the rocks almost **completely dehydrated**
- By ca.420 Ma, tectonic burial during the Caledonian orogeny pushed them to eclogite conditions: 1.5 Gpa, 650-700°C [Gt2 + Omp ± Ky ±Zo ± Phe]

- Hydrous minerals in eclogite assemblages indicate water was reintroduced
- Path to eclogite P-T conditions was very different from that of 'juvenile' ocean crust in subduction

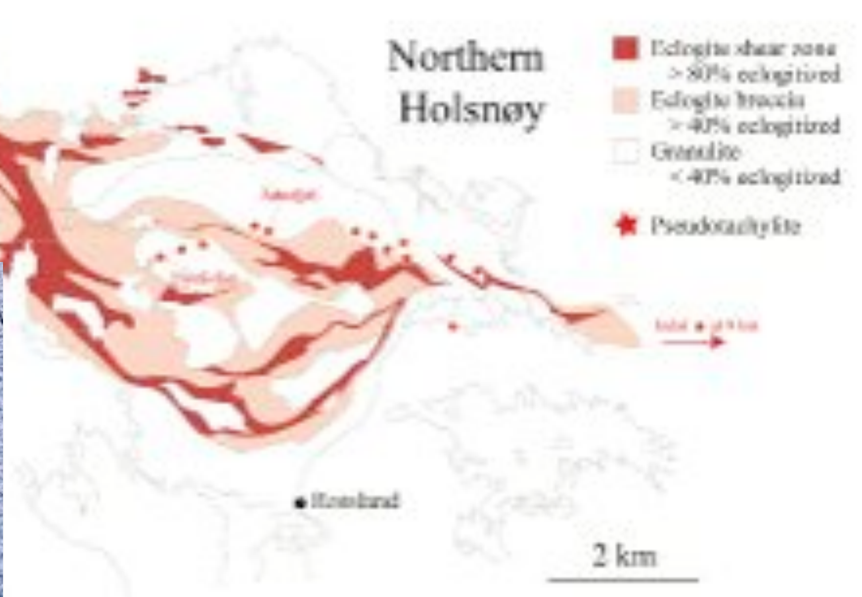


Based on work by Austrheim, Bjørnerud, Boundy, Erambert, Fountain, Jamtveit, Klaper, Lund, et al.

Eclogite metamorphism caught in action

Eclogite metamorphism was patchy and heterogeneous - nowhere entirely complete

H_2O apparently triggered the granulite-eclogite transition.
Critical for reaction
Albite → Jadeite + Qtz
(Hacker 1996)

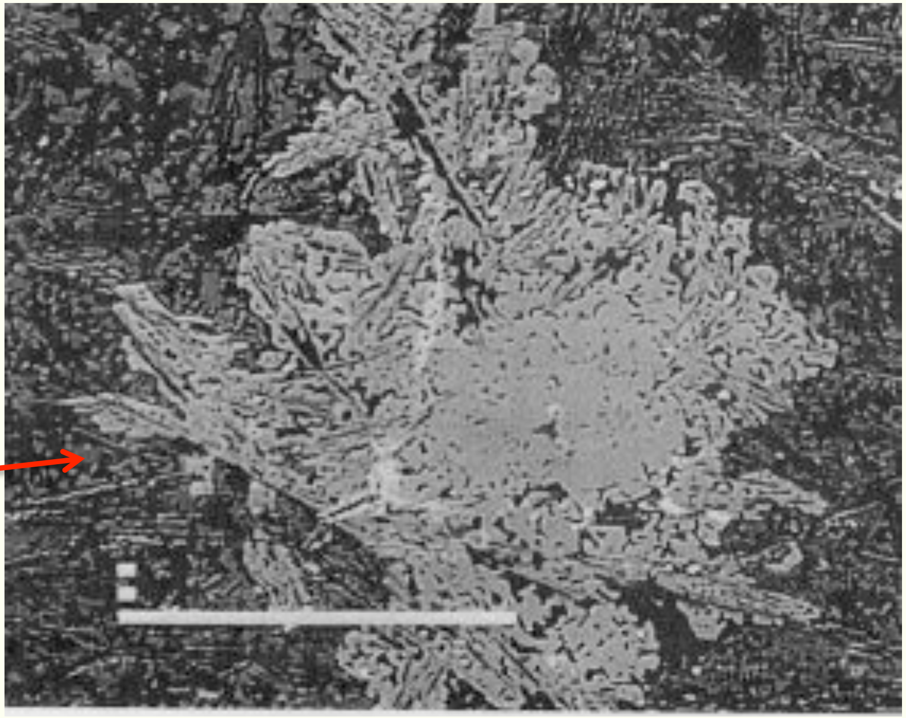


Eclogite 'front' adjacent to fracture in granulite

Volume decrease upon granulite-eclogite conversion was ca. 10%

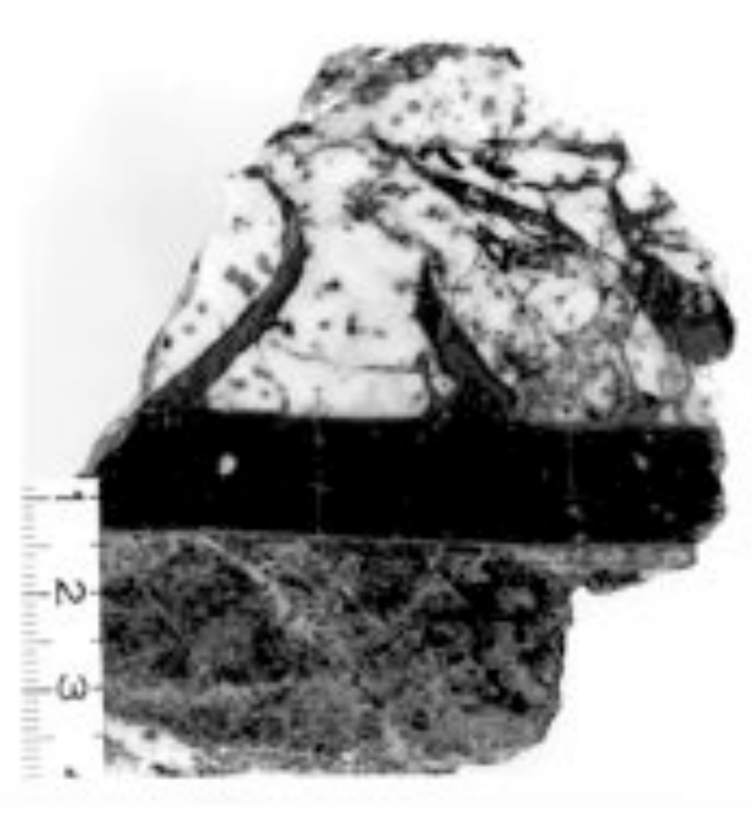
Eclogite-facies pseudotachylyte in Bergen Arcs

Even at eclogite P-T conditions (> 50 km depth), the dry metastable granulite was strong enough to fail seismically along gneissic foliation surfaces



Dendritic garnet in pseudotachylyte nucleated around kyanite crystals → Earthquakes occurred at eclogite-facies depths

Physical characteristics of the Holsnøy pseudotachylytes

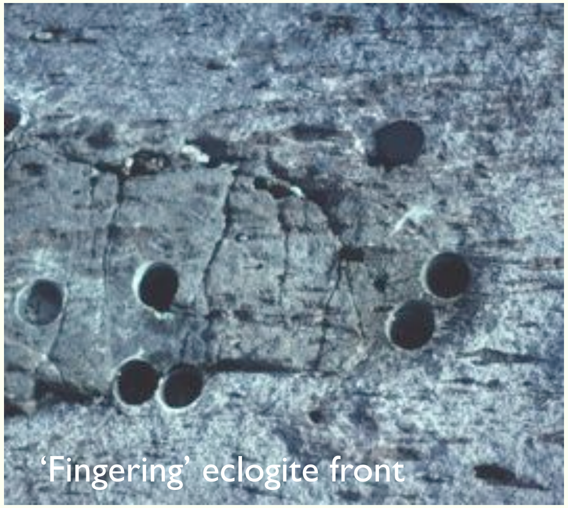


- Relatively simple injection vein geometries
- Little brecciation or cataclasis except at dilational jogs
- Formed only at earliest stages of deformation process – **no pseudotachylyte in eclogitized rock**

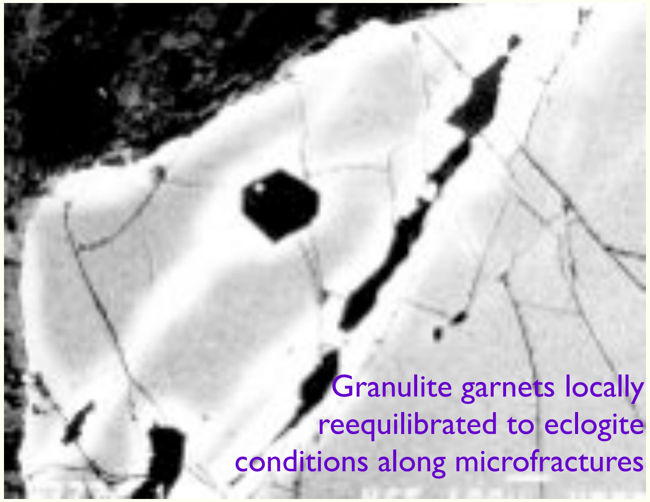
Interplay between seismicity, fluids and metamorphism on Holsnøy

Stage 1. One or more large earthquakes fractures granulite, forming pseudotachylyte and allowing fluids to enter.

Planar eclogite front



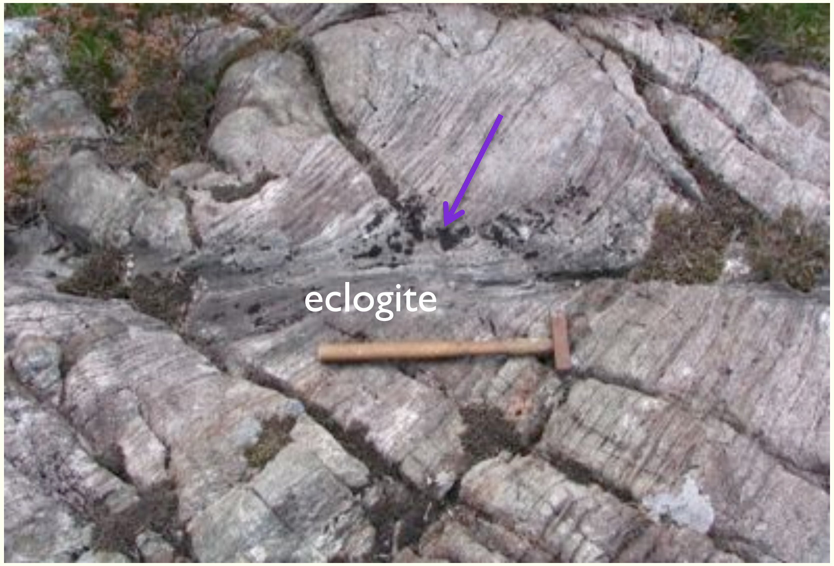
‘Fingering’ eclogite front

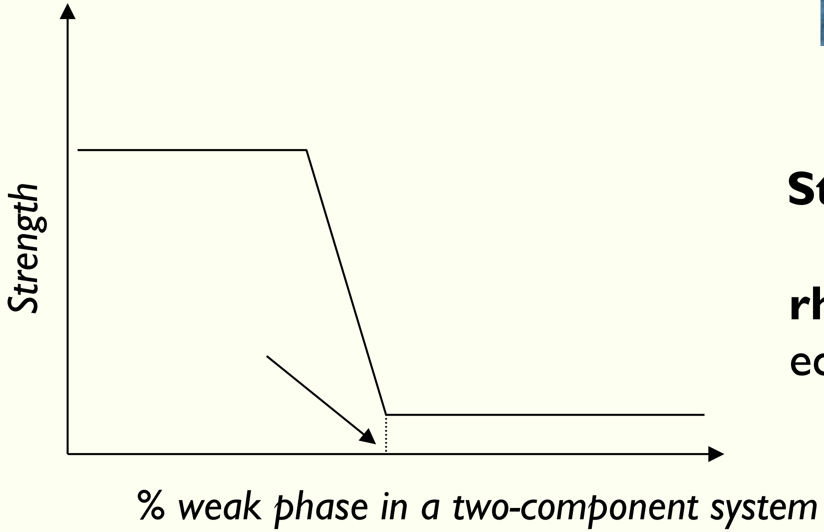


Granulite garnets locally reequilibrated to eclogite conditions along microfractures

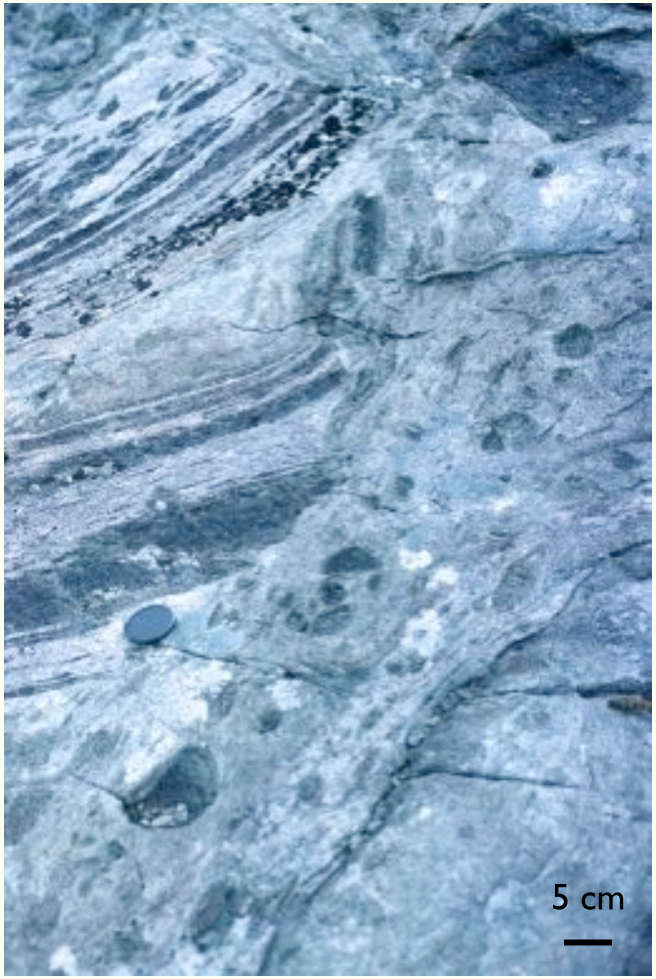
Stage II. Fluids trigger eclogitization in metastable granulite along **self-propagating reaction fronts**: Shrinkage causes microfracturing, allowing fluids to make further inroads, causing more eclogite formation.

Stage III. Relatively weak, hydrous eclogite localizes shear strain.



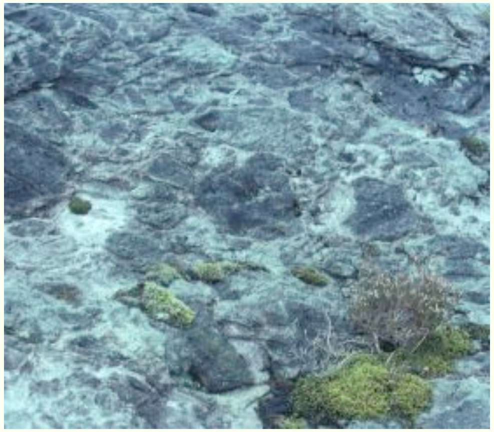


Stage IV. Eclogite shear zones grow and coalescse until rock mass reaches **rheologically critical fraction** of weak eclogite, and can no longer fail seismically.



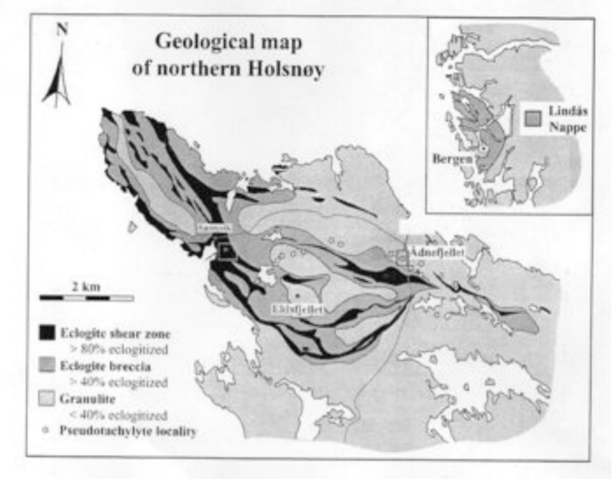
5 cm

Stage V. Once fracturing ceased, fluids could no longer gain entry to areas of unconverted granulite, leaving relict pods surrounded by eclogite. Patchiness of conversion is seen at many scales.



1 m

10 m



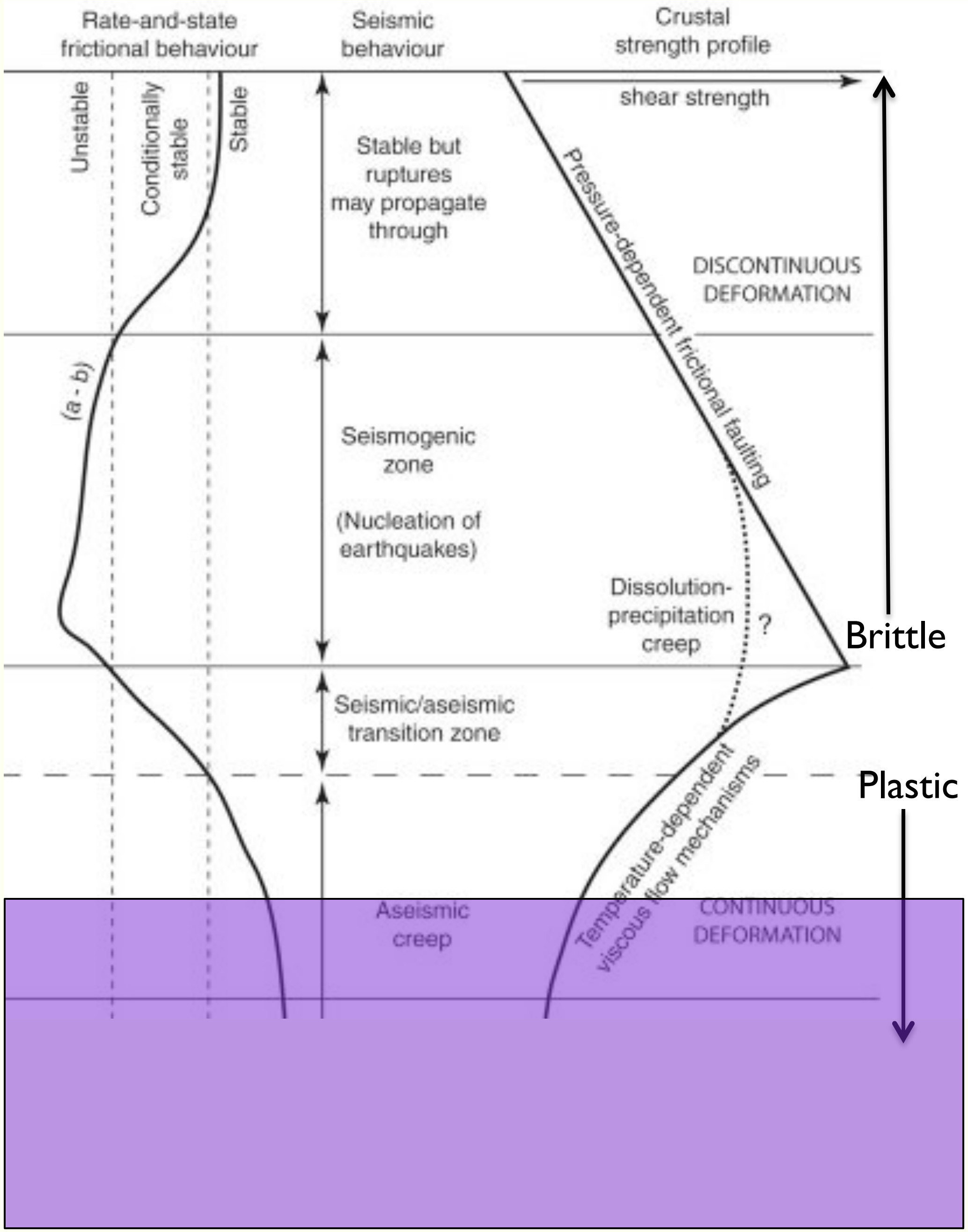
1 km

Inferences from the Holsnøy pseudotachylytes:

Dry granulites were strong and able to fail seismically even at eclogite depths far below the brtitle-plastic transition

Large earthquakes admitted fluids that triggered over-stepped metamorphic reactions in an initially self-amplifying but ultimately self-limiting process

Infiltration of water only *indirectly* stopped the formation of pseudtachylyte (change in rock rheology, not thermal pressurization)



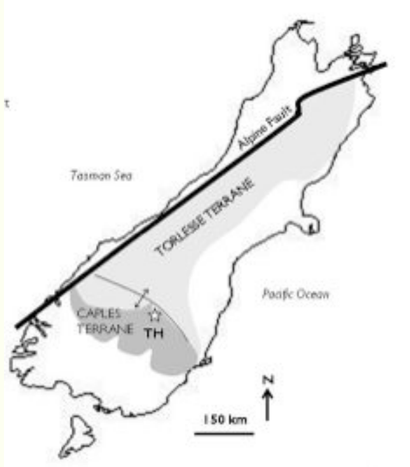
Case study III: Greenschist-facies pseudotachylytes in schists, Tucker Hill, South Island, New Zealand

Host rock: Permian-Jurassic Otago schists - turbidites deformed and metamorphosed in early Cretaceous Rangitata orogeny

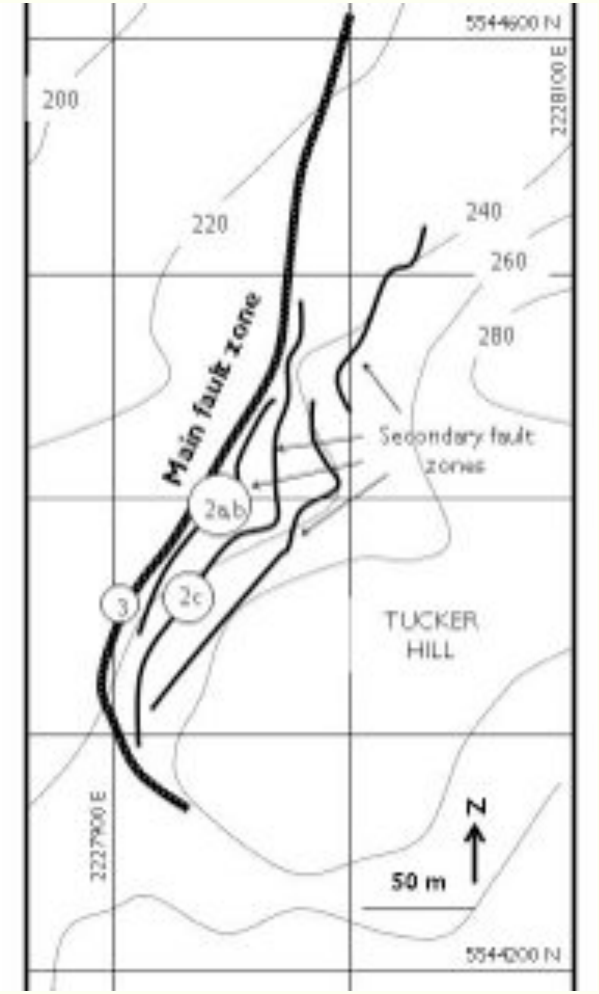
Lower-middle greenschist facies assemblages:
Qtz + Ms + Chl (+/- Plag + Ep + Graph)

(Barker et al., *NZJGG*, 2010; Bjornerud, *Tectonophysics* 2010)

Pseudotachylyte at Tucker Hill formed in late Cretaceous time (ca. 95 Ma) as rocks were being exhumed along a low-angle normal fault zone

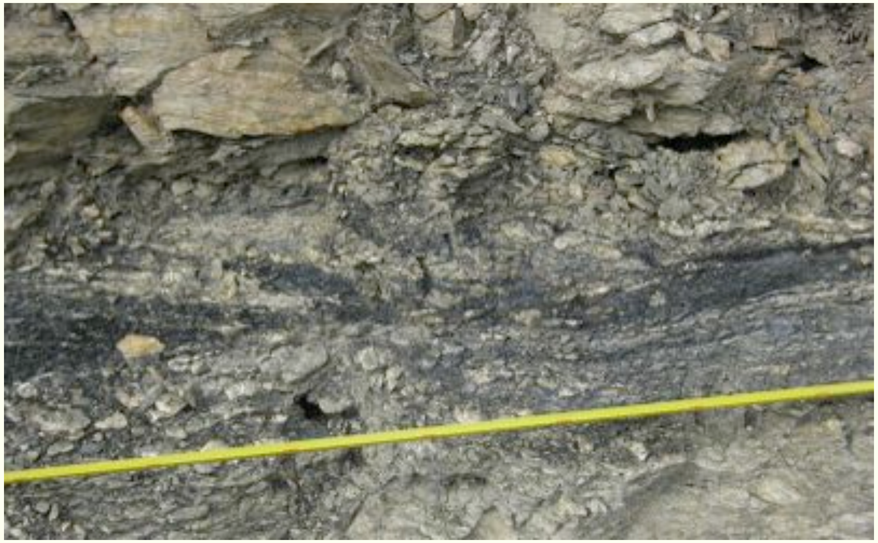


At outcrop and thin section scales, **complex relationships between multiple generations of pseudotachylyte and cataclasite**

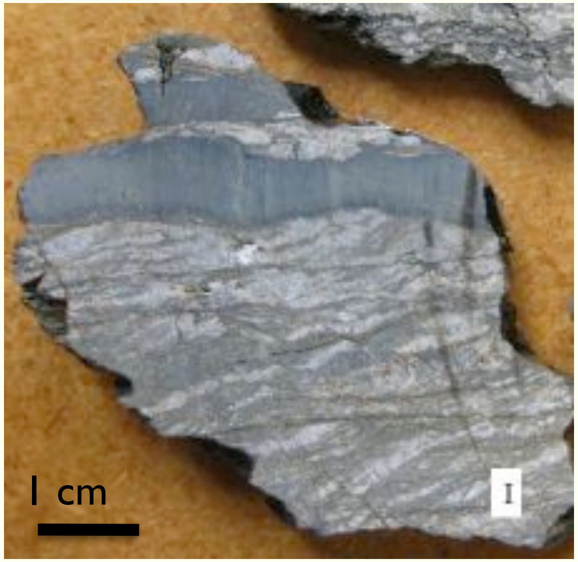


Pseudotachylyte & cataclasite at Tucker Hill

Pseudotachylyte fault veins somewhat irregular, not always parallel to pre-existing foliation



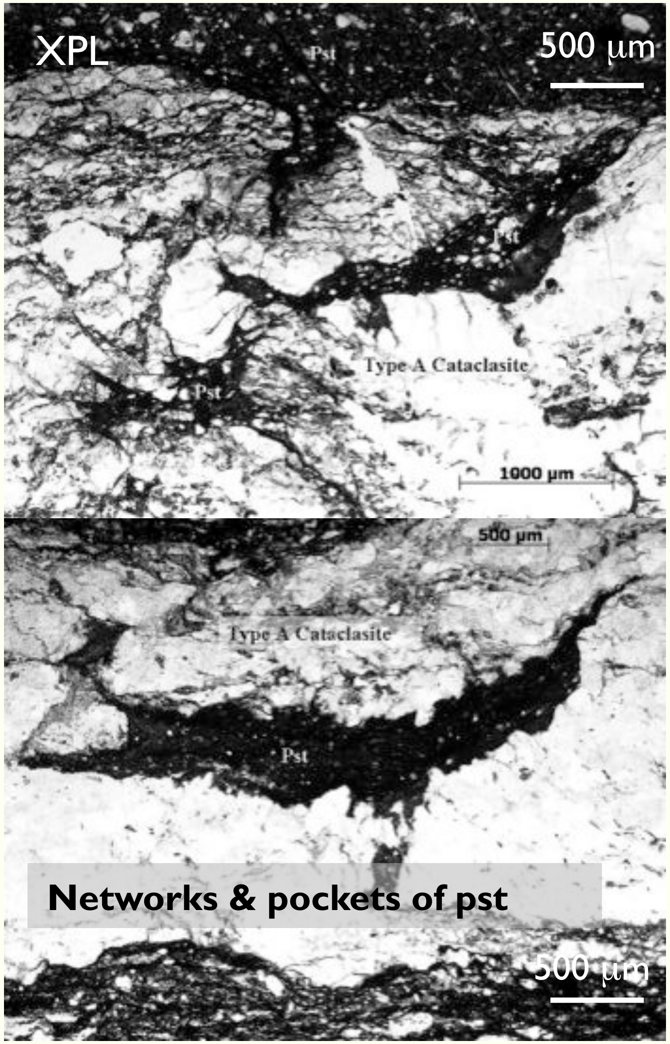
Black cataclasite + pseudotachylyte (?) interfingering with cataclasized rock



Intrusive 'flame' structures of cataclasite above thin pst vein

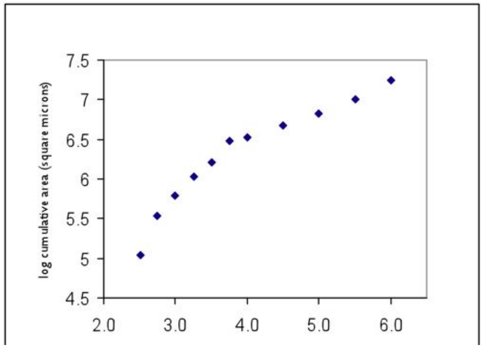
Two distinct types of cataclasite at Tucker Hill

Pseudotachylyte pervasively intrudes host ('**Type A**') cataclasite – geometries more complex than simple injection veins



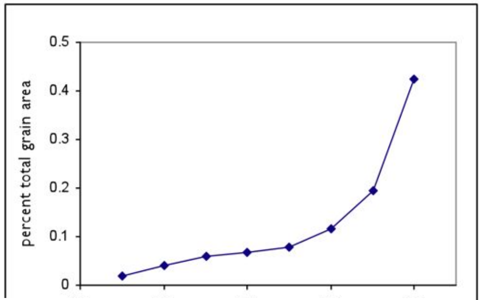
Networks & pockets of pst

Bi-fractal distribution typical of frictional wear cataclasis



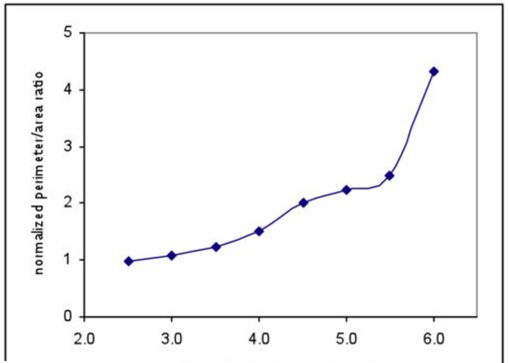
Log [cumulative grain area] vs. log grain size

Unimodal grain size distribution



Fraction of total grain area vs. log grain size

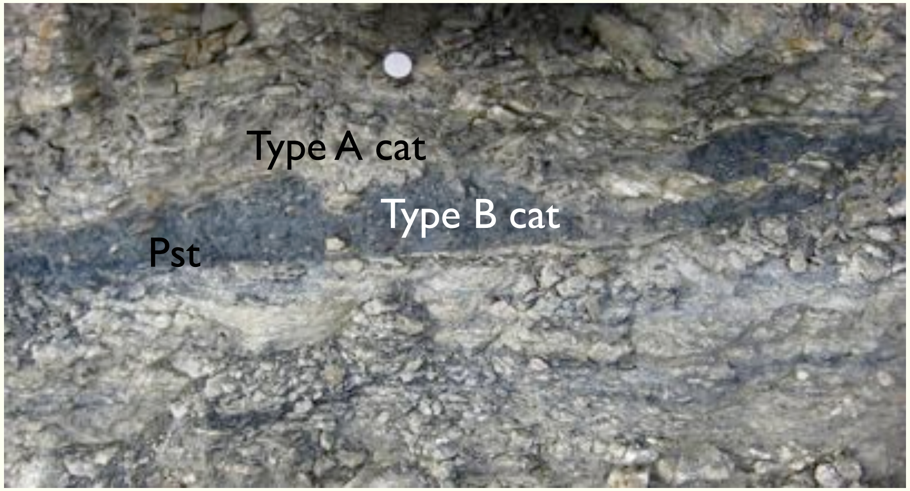
Smaller grains are most rounded, as expected in frictional wear



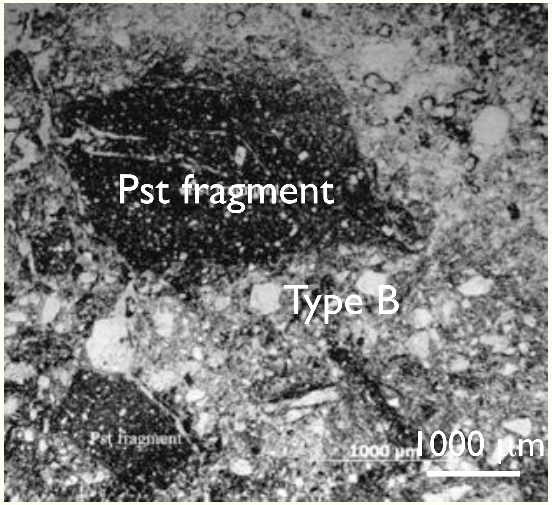
Normalized perimeter/area ratio vs. log grain size

Two distinct types of cataclasite at Tucker Hill

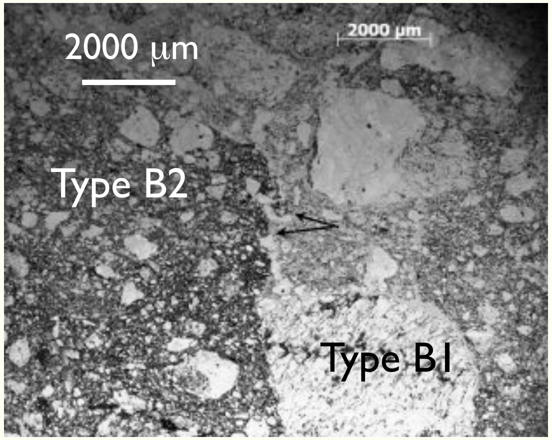
Type B cataclasite intrudes Type A,



includes pseudotachylyte fragments,



but in some cases is also intruded by pseudotachylyte,

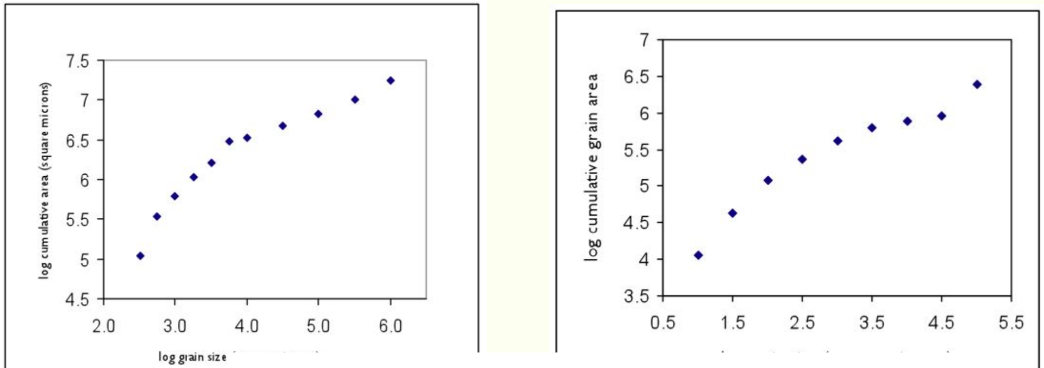


and occurs as multiple generations.

Type A cataclasite

Type B cataclasite

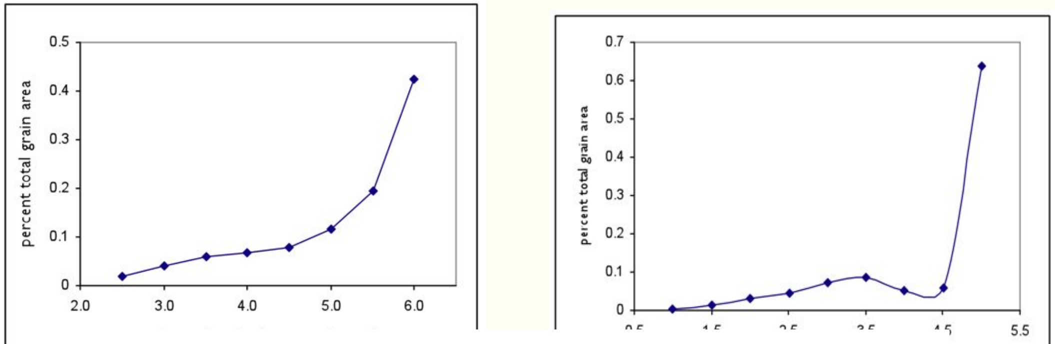
Bi-fractal distribution typical of frictional wear cataclasis



Non-fractal grain size distribution

Log [cumulative grain area] vs. log grain size

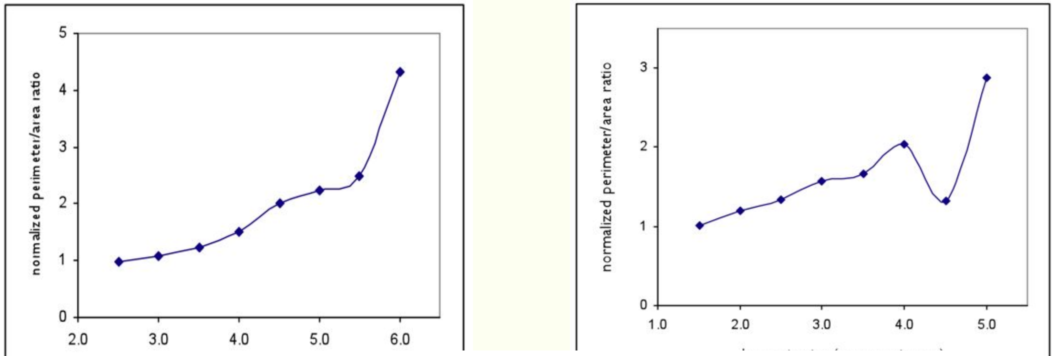
Unimodal grain size distribution



Slightly bimodal grain size distribution

Fraction of total grain area vs. log grain size

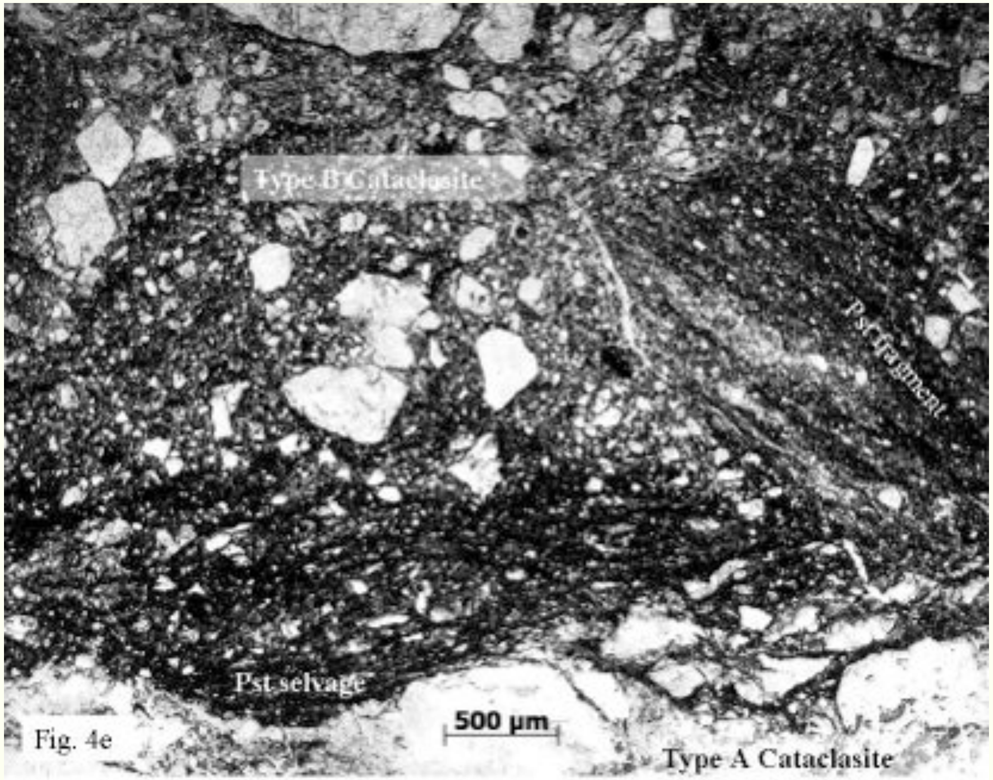
Smaller grains are most rounded, as expected in frictional wear



Non-systematic clast shape vs. size relationships →

Mixing of two populations of grains

Normalized perimeter/area ratio vs. log grain size



Textural relationships between pseudotachylytes and cataclasites at Tucker Hill indicate:

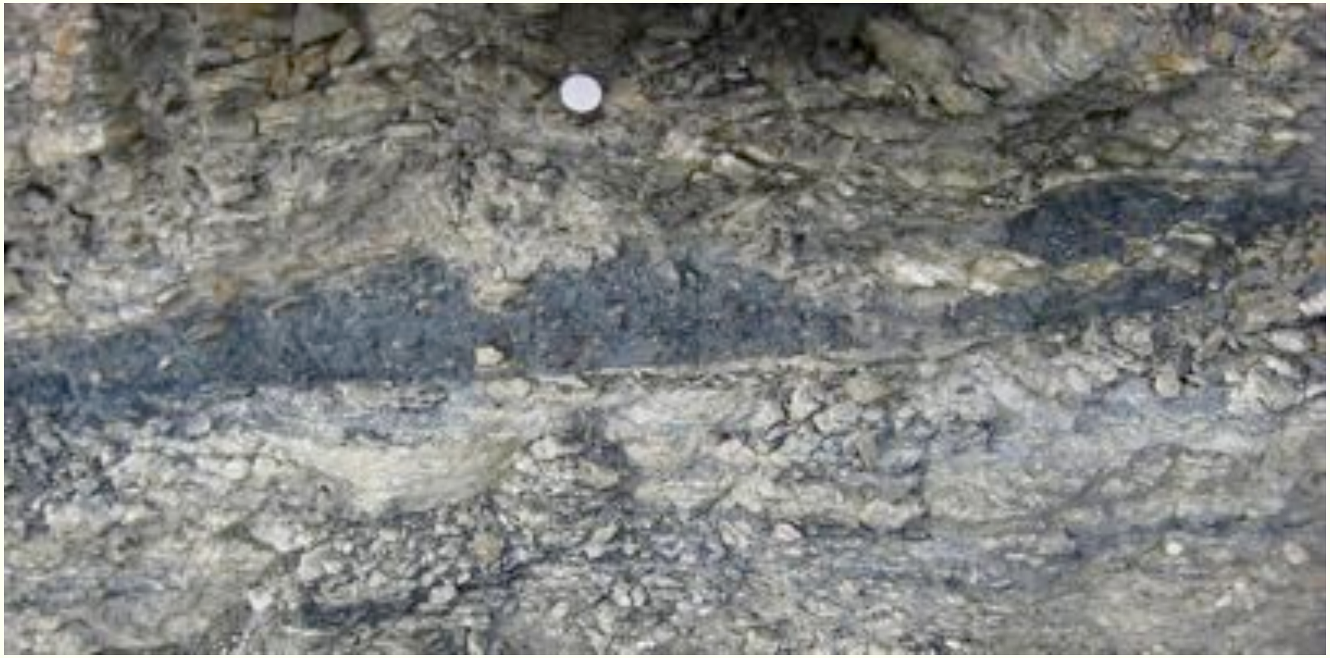
- ‘Type A’ cataclasites formed first and created permeable rock mass
- Pseudotachylyte pervasively intruded ‘Type A’ cataclasites
- Mobile/fluidized (thermally pressurized?) ‘Type B’ cataclasites and pseudotachylyte formed in alternation

Rocks at Tucker Hill challenge conventional wisdom about conditions for pseudotachylyte formation:

- No evidence that the rocks were particularly dry
(greenschist facies; veins and hydrous minerals; evidence of pressure dissolution)

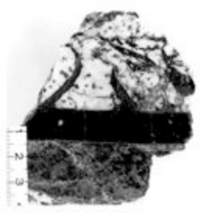
- No evidence that rocks were particularly 'tight'
(efficient infiltration of pseudotachylyte into Type A cataclasite)

- Both melting and thermal pressurization seem to have occurred in the fault zone
(alternating events or different times in single events)



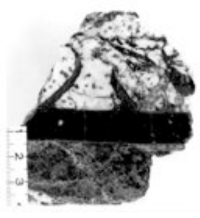
Similar observations have been made along the Nojima Fault zone (Otsuki et al., *JGR*, 2003) and in an accretionary prism complex in Japan (Ujiie et al., *JSG*, 2007)

DRY PSEUDOTACHYLYTES



- Pseudotachylyte generation zones controlled by older fabrics → rest of rock mass is strong
- Relatively little cataclasite; fragmentation limited to melt-engulfed ‘rip-outs’ on fault vein margins and implosion breccias in dilational jogs
- Simple injection vein geometries
- Only formed early in fault zone history

DRY PSEUDOTACHYLYTES



- Pseudotachylyte generation zones controlled by older fabrics → rest of rock mass is strong
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- Simple injection vein geometries
- Only formed early in fault zone history

WET PSEUDOTACHYLYTES

- Pseudotachylyte generation zones not consistently controlled by older fabrics → all of rock mass equally weak
- Abundant cataclasite – rock was cataclasized prior to pseudotachylyte generation
- Complex injection vein geometries
- Formed for an extended period of fault zone’s history

The key may lie in the relative rates at which
heat and fluids escape from a fault zone

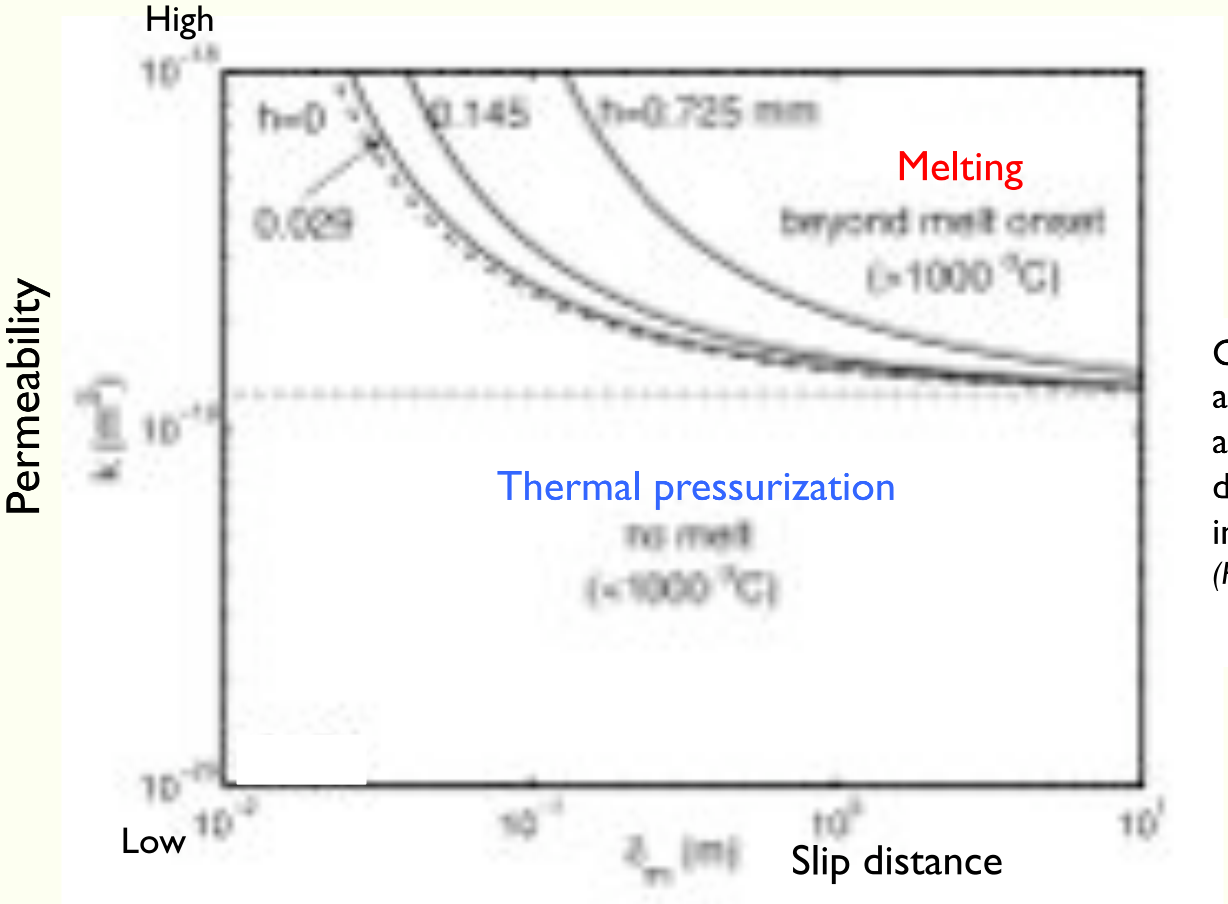
Thermal pressurization occurs when
hydraulic diffusivity < thermal diffusivity

i.e., the rate of fluid loss is less than the rate of heat loss

Melting occurs when thermal diffusivity < hydraulic diffusivity

i.e., the rate of heat loss is less the rate of fluid loss
(wet pseudotachylyte)
Fluids leaving fault zone may take away some heat,
but draining re-establishes frictional contact
OR
fluids are simply absent (dry pseudotachlyte)

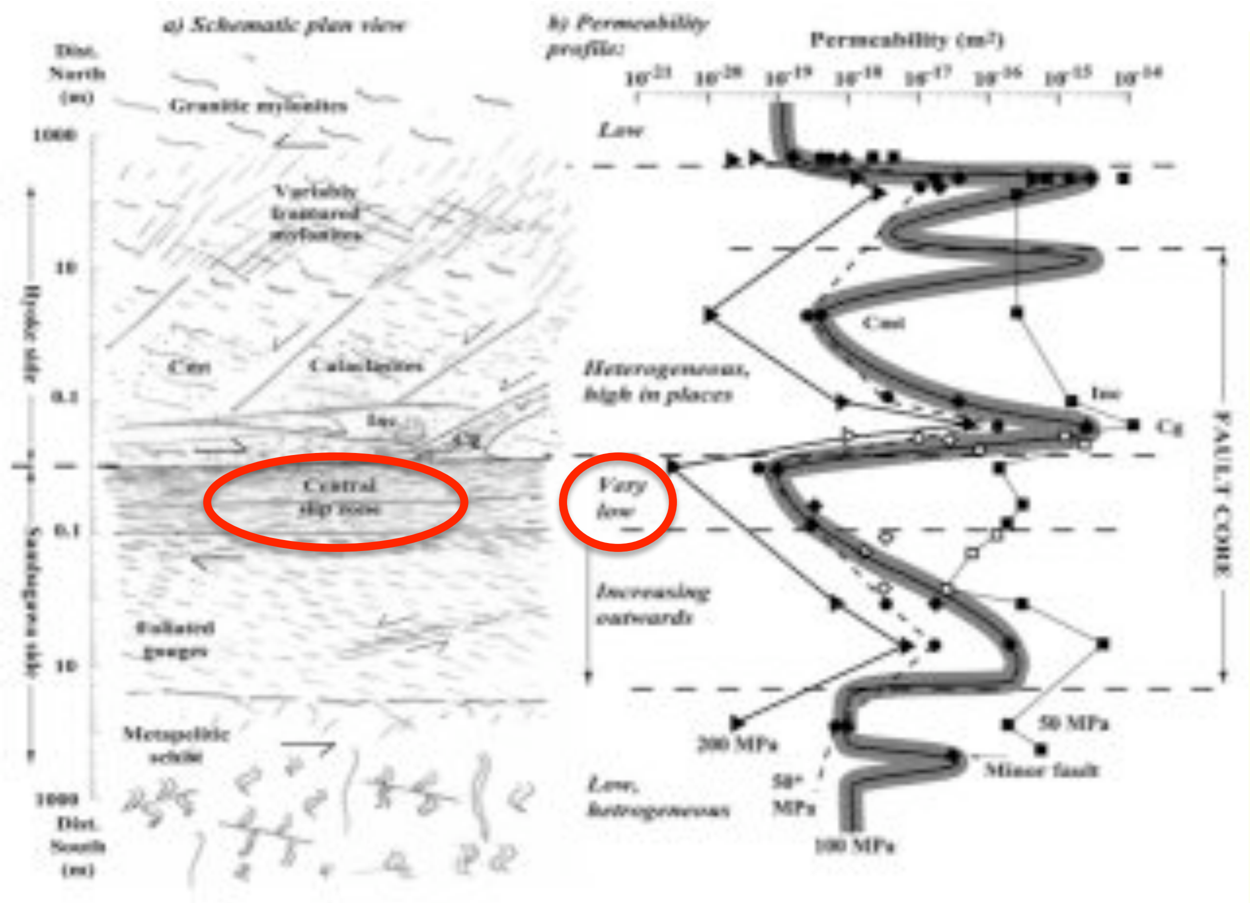
In the presence of fluids, melting can happen only when fault zone rocks are *permeable*



Calculated conditions for melting as a function of rock permeability (k) and fault slip (δ), for fault zones of different thickness (h). Assumed initial temperature of 220C.
(Rempel & Rice, JGR 2006)

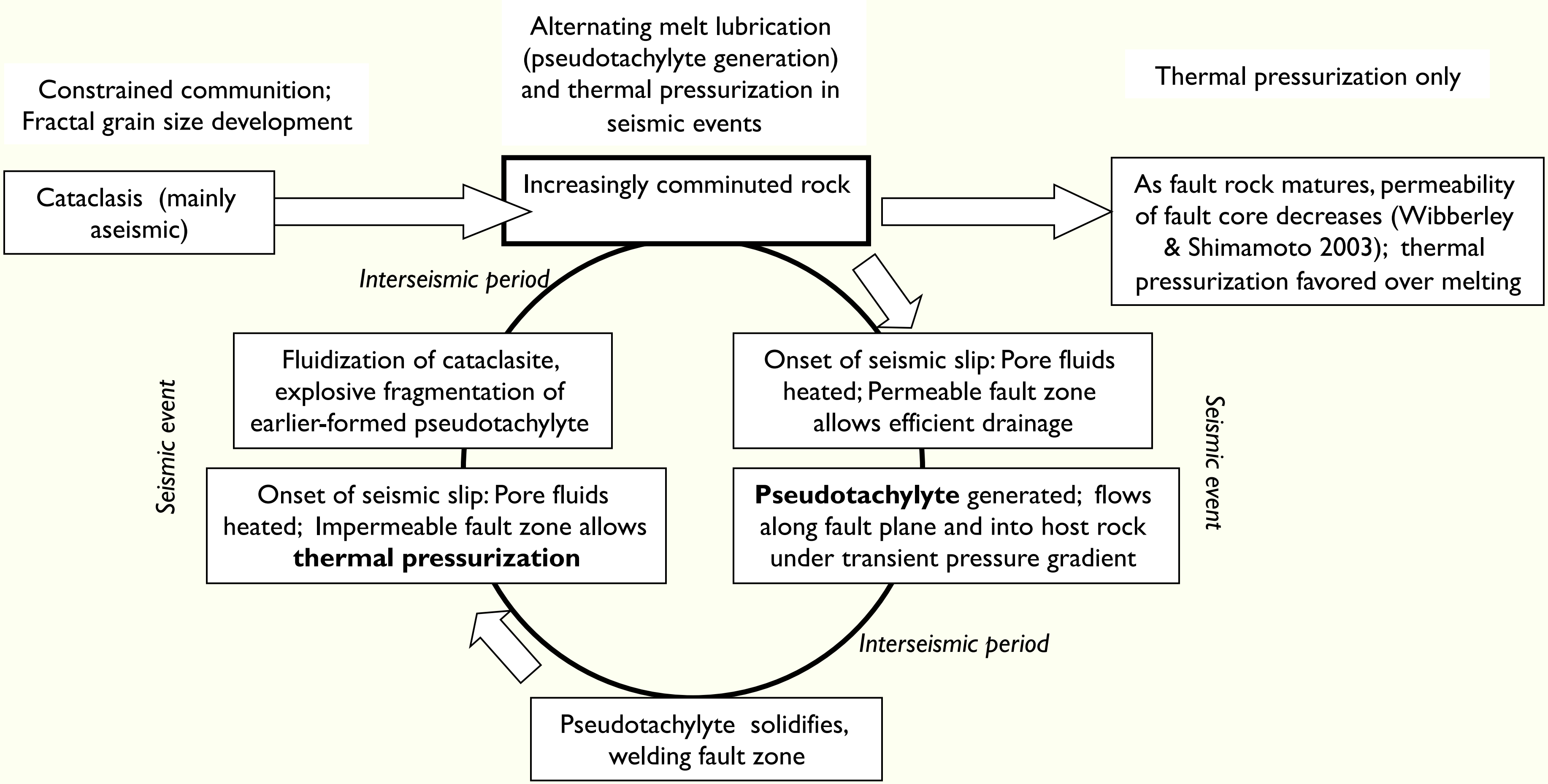
And hydraulic diffusivity (~permeability) of fault rocks evolves over the life of a fault zone…

Permeability of fault zone rocks varies with maturity.
Early cataclasites may have high (if heterogeneous) permeability, but as fault zone ages, grain size and permeability tend to decrease.



Permeability structure of Median Tectonic Line, Japan
(Wibberley and Shimamoto, J. Struct. Geol., 2003)

Inferences from the Tucker Hill pseudotachylytes:
In the presence of fluids, melting and thermal pressurization may alternate as long as fault zone remains permeable



Constrained communition; Fractal grain size development

Cataclasis (mainly aseismic)

Alternating melt lubrication (pseudotachylyte generation) and thermal pressurization in seismic events

Increasingly comminuted rock

Thermal pressurization only

As fault rock matures, permeability of fault core decreases (Wibberley & Shimamoto 2003); thermal pressurization favored over melting

Interseismic period

Onset of seismic slip: Pore fluids heated; Permeable fault zone allows efficient drainage

Seismic event

Pseudotachylyte generated; flows along fault plane and into host rock under transient pressure gradient

Interseismic period

Pseudotachylyte solidifies, welding fault zone

Onset of seismic slip: Pore fluids heated; Impermeable fault zone allows **thermal pressurization**

Seismic event

Fluidization of cataclasite, explosive fragmentation of earlier-formed pseudotachylyte

Two distinct 'windows' for pseudotachylyte generation

DRY PSEUDOTACHYLYTE

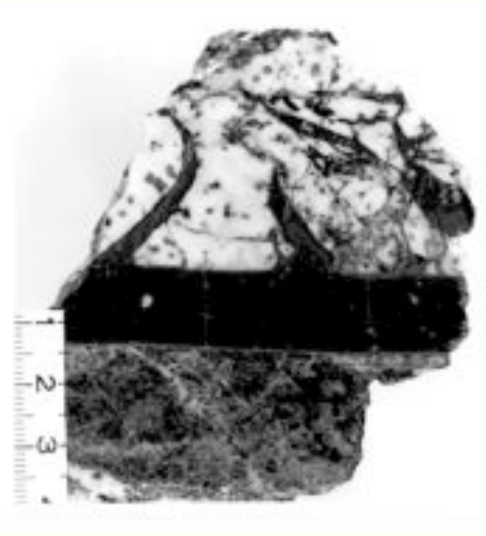
(Holsnøy, 12-Foot Falls)

Initial/early rupture of dry, intact, low-permeability rock. Melting occurs under conditions of high shear resistance, commonly along pre-existing planes of weakness. Pst window closes once water gets *in.* Fluid infiltration may be limited by continuing mylonitization.

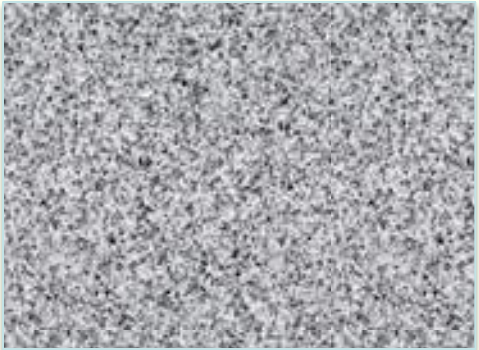
WET PSEUDOTACHYLYTE

(Tucker Hill, NZ)

Secondary rupture of weak rocks in which fluids are present. Melting occurs after the formation of a 'leaky' cataclastic damage zone but before the development of a fine-grained, impermeable fault core. Pst window closes when water can't get *out*.

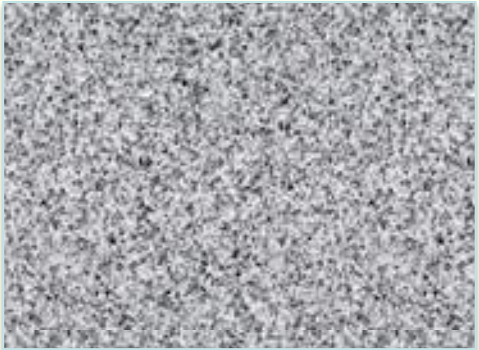


DRY PSEUDOTACHYLYTE:

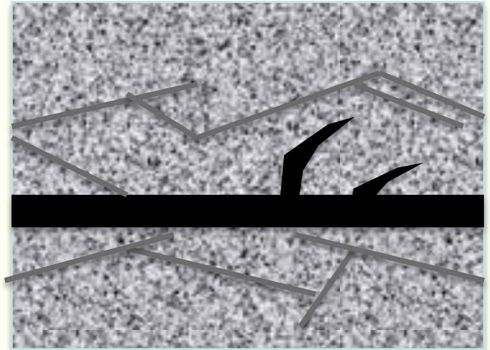


Dry, intact, low-permeability rock

DRY PSEUDOTACHYLYTE:

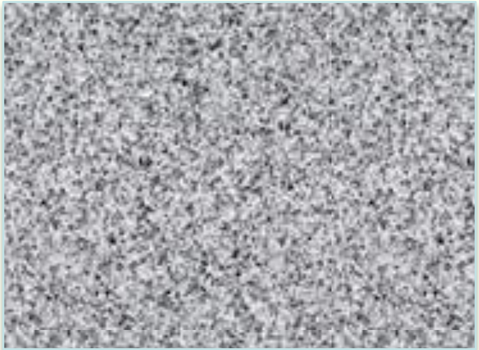


Dry, intact, low-permeability rock



Initial rupture & slip creates frictional melt and damaged zone

DRY PSEUDOTACHYLYTE:



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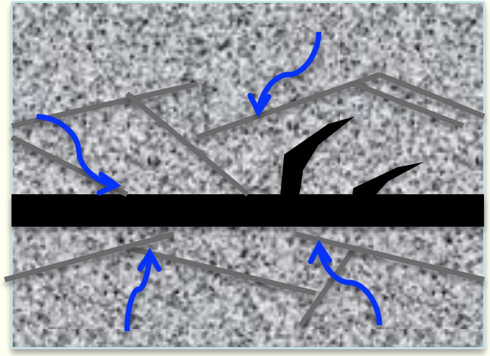
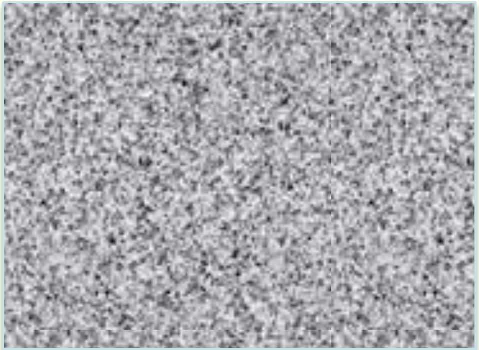


Fluids enter fault zone; frictional melting suppressed in future events by thermal pressurization (unless sealed by mylonitization)

DRY PSEUDOTACHYLYTE:



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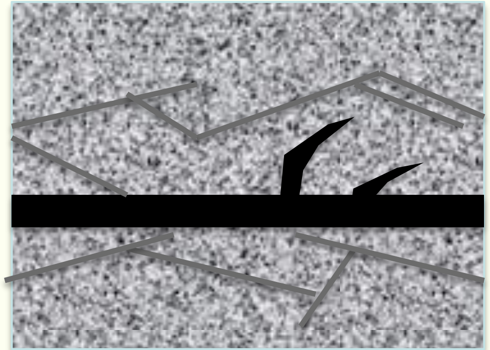

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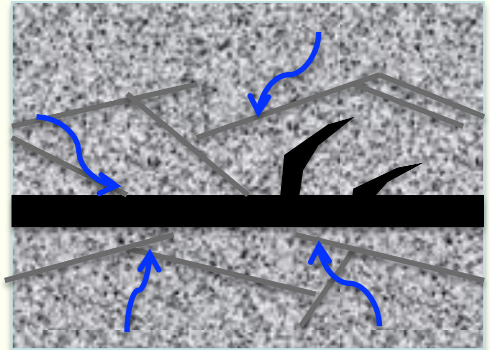
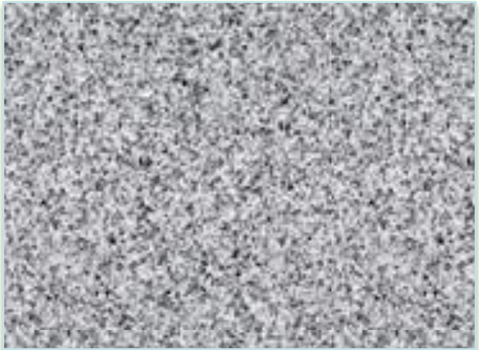


Fluids enter fault zone; frictional melting suppressed in future events by thermal pressurization (unless sealed by mylonitization)

WET PSEUDOTACHYLYTE:

Fluid-bearing, permeable rock. perhaps already cataclasized

DRY PSEUDOTACHYLYTE:



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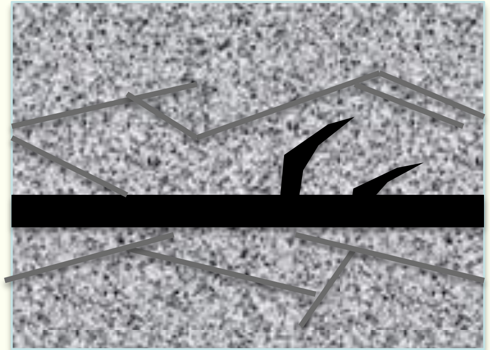

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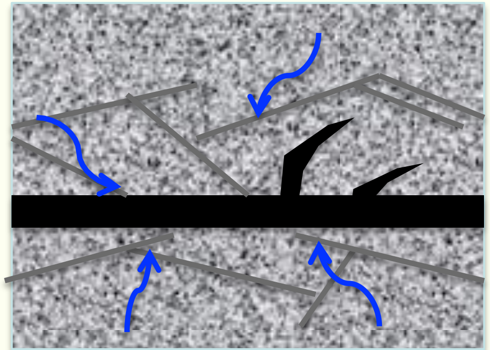

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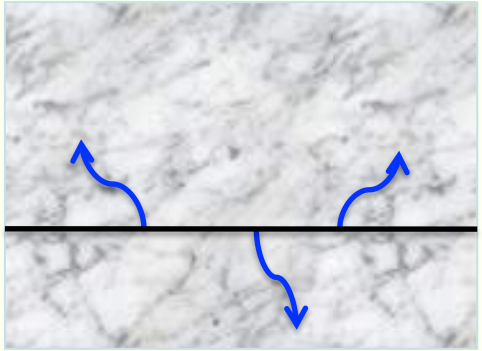
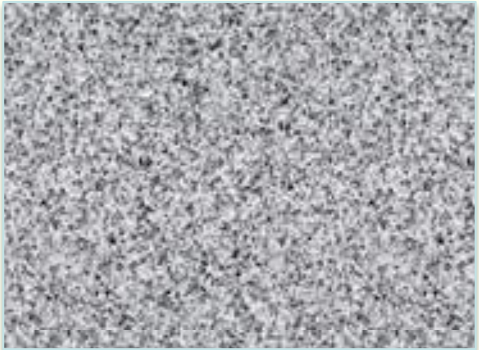
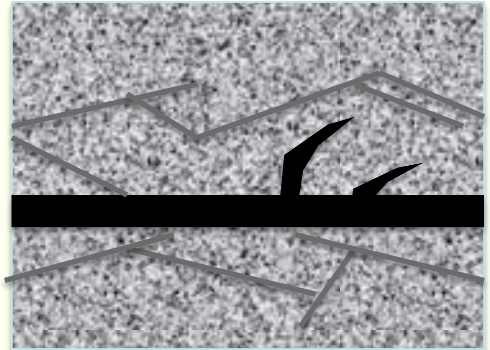


Slip causes thermal pressurization; fluids escape into surrounding rock.

DRY PSEUDOTACHYLYTE:



Dry, intact, low-permeability rock



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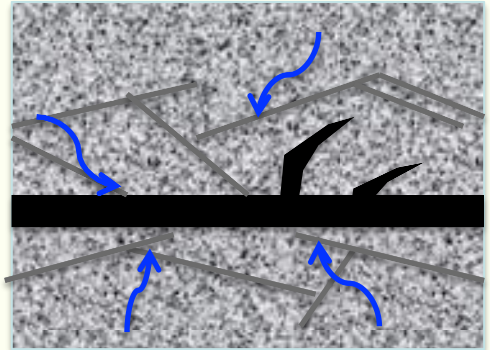

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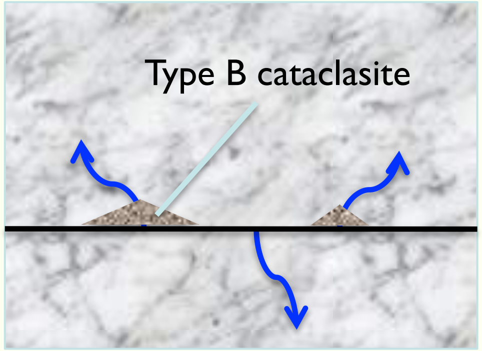

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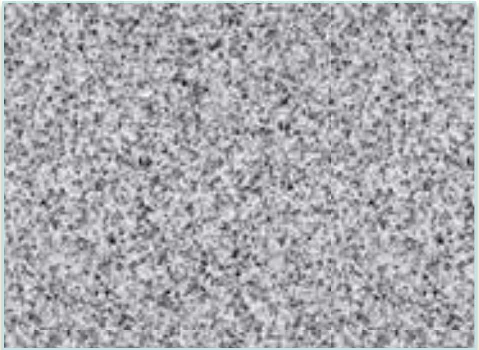
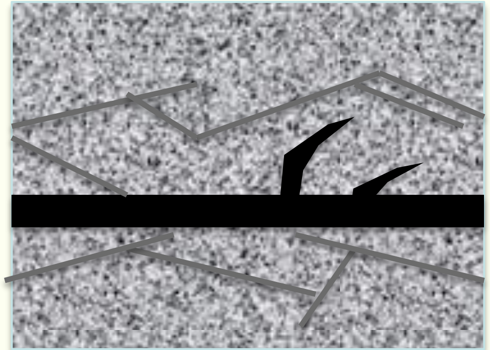
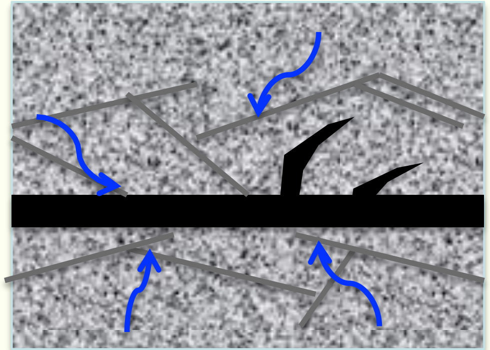


Dry, intact, low-permeability rock



Initial rupture & slip creates frictional melt and damaged zone



Fluids enter fault zone; frictional melting suppressed in future events by thermal pressurization (unless sealed by mylonitization)

WET PSEUDOTACHYLYTE:

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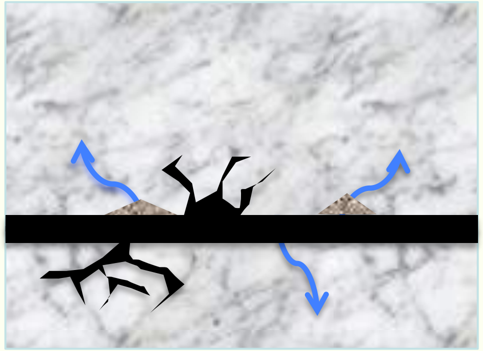
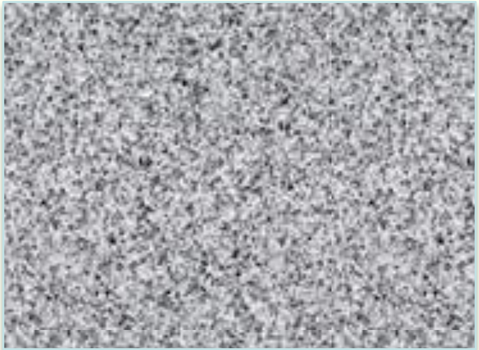
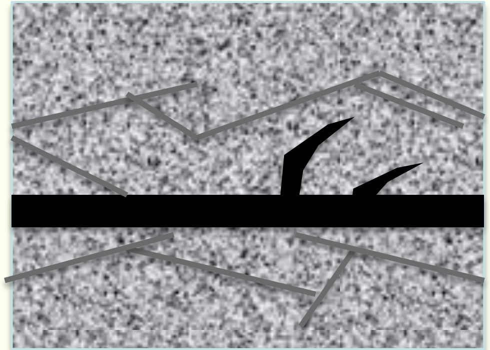


Slip causes thermal pressurization; fluids escape into surrounding rock. Frictional contact re-established, allowing melting.

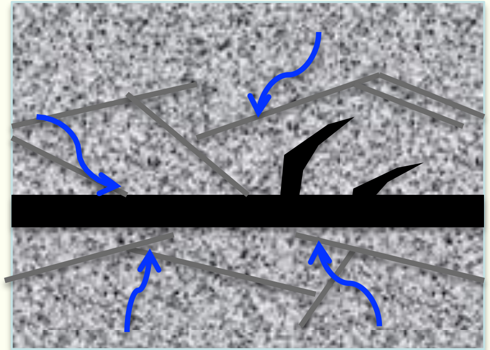
DRY PSEUDOTACHYLYTE:



Dry, intact, low-permeability rock



Initial rupture & slip creates frictional melt and damaged zone



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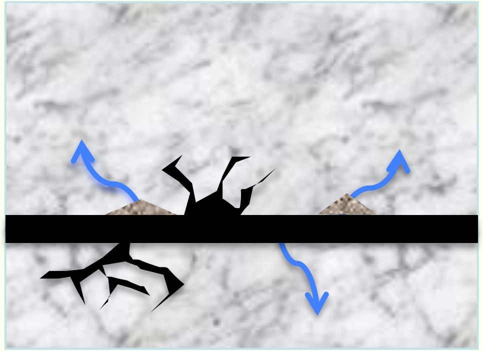

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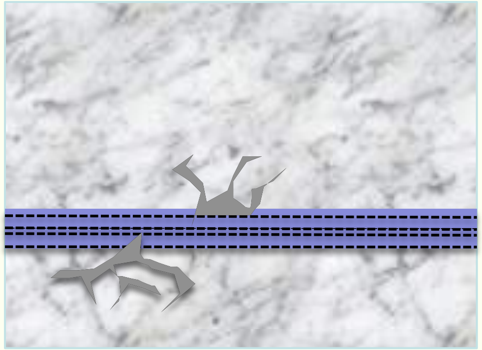


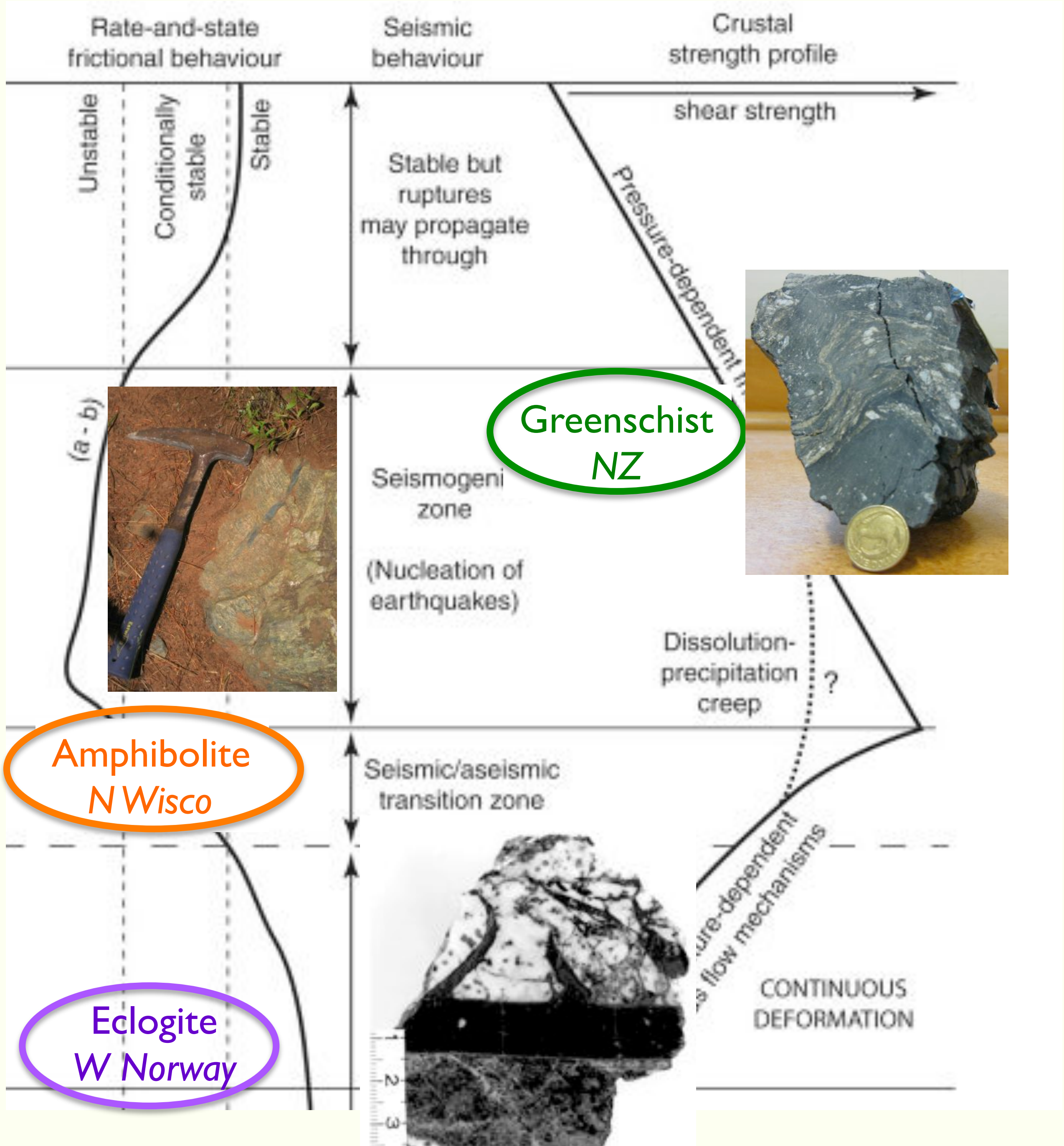
Cycle continues until fault core permeability gets too low for fluids to escape

Insights from the 3 case studies

Earthquakes are not all alike phenomenologically!

Interactions between rocks and fluids depend on depth, rock type, and antecedent history

As fault zones evolve, velocity weakening mechanisms may change over time



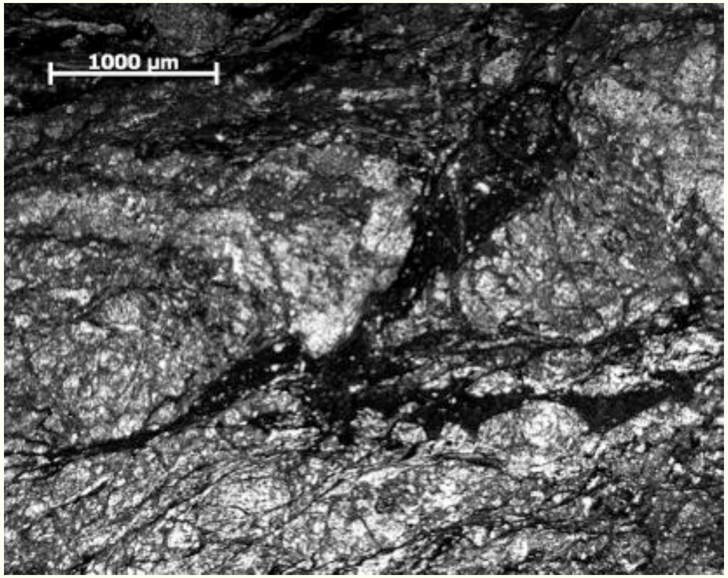
Pseudotachylyte – glassy rock representing frictional melt – is considered by many geologists to be the only unambiguous indicator of ancient earthquakes. Because its high temperature of formation requires frictional contact between rock surfaces, the presence of fluids in fault zones has been thought to suppress its formation since these fluids would become thermally pressurized during a seismic event and thus reduce the frictional resistance along the slip surface. Natural exposures of pseudotachylyte representing three different levels of the crust reveal that the interplay between fluids and pseudotachylyte formation is in fact more complex. Pseudotachylytes formed at eclogite-facies conditions (ca. 50 km depth) in very dry granulite-facies rocks in the Scandinavian Caledonides in western Norway reveal how earthquakes may provide conduits for aqueous fluids and trigger overstepped metamorphic reactions which in turn change rock rheology. Amphibolite-facies pseudotachylytes in an early Proterozoic fault zone in northern Wisconsin show mutually cross-cutting relationships with both mylonites and quartz-hornblende veins, indicating that alternating episodes of plastic deformation, seismic slip, fracture, and high-temperature fluid flow occurred in the middle crust (ca. 20 km). Greenschist-facies pseudotachylytes and cataclasites along a Cretaceous low-angle normal fault in turbidites on New Zealand's South Island show that frictional melting can occur even in very hydrous rocks in the upper crust (ca. 10 km) if fracture networks allow fluids to escape the fault zone over the timescale of a seismic event. Collectively, these observations may aid in the interpretation of real-time seismic records and perhaps contribute to seismic hazard assessments in different modern tectonic settings.

However, hydraulic diffusivity is related not only to the permeability of the rocks adjacent to the fault surface but also to capacity of the zone to 'absorb' expanding fluids

Just as: *Thermal diffusivity* = $k/c\rho$ = $\frac{\text{Thermal conductivity}}{\text{Specific heat x Density}}$

Similarly, *Hydraulic diffusivity* = K/S = $\frac{\text{Hydraulic conductivity}}{\text{Specific storage}}$

Specific storage



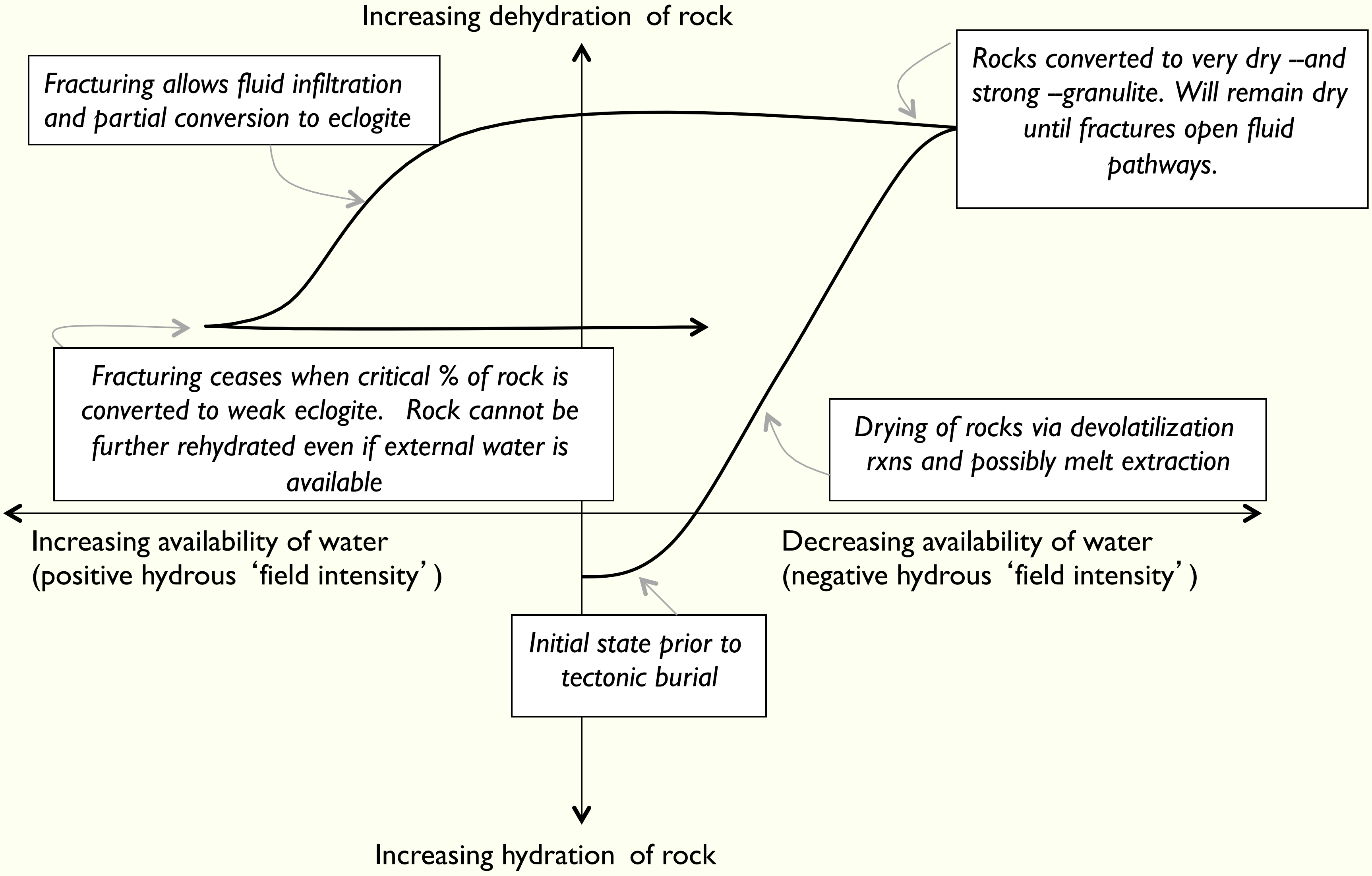
Transient creation of dilatant space during a seismic event could cancel out high permeability, making it less likely that a fault will drain over the time scale of slip

The most efficiently drained fault zones (most likely to generate pseudotachylyte) will be those that have high intrinsic permeability but low co-seismic dilatancy (pre-fractured)– a combination that may exist for only a brief period in a fault's evolution

Rheologically critical fraction of weak phase in a two-component system

	Rock type	**Range**	**Most typical value/ middle of range**
Arzi (1978)	Magma+Crystals (RCMP)	10-30%	20%
Vigneress&Tikoff (1999)	Magma+Crystals (liquid escape threshold)	20-25%	22.5%
Gilotti (1992)	Mylonites	10%-50%	20-30%
Ross et al. (1987)	Anhydrite-Halite	20-25%	22.5%
Escartin	Dunite-Serpentinite	15%	15%

Dehydration/rehydration ‘hysteresis’ loop for mafic lower crust: Dehydration is forever



Increasing dehydration of rock

Fracturing allows fluid infiltration and partial conversion to eclogite

Rocks converted to very dry --and strong --granulite. Will remain dry until fractures open fluid pathways.

Fracturing ceases when critical % of rock is converted to weak eclogite. Rock cannot be further rehydrated even if external water is available

Drying of rocks via devolatilization rxns and possibly melt extraction

Increasing availability of water (positive hydrous ‘field intensity’)

Decreasing availability of water (negative hydrous ‘field intensity’)

Initial state prior to tectonic burial

Increasing hydration of rock

Model scenario	Model parameters	Volumes of rock types produced	Process Duration from onset of fracturing
4. **Massive single seismic event**	Single episode of Fracture & Cataclasis creates 5*10^{-5} vol. units of fractured rock	**PG = 48%** **FG = 1%** **LE = 3%** **EB = 27%** **E = 22%**	10,000 yrs
5. **Rapid crack healing** (aseismic)	Transit time for Newly Fractured Granulite = 0.1 kyr (100 yrs), with constant fracture rate of 10^{-6}/ kyr	**PG = 67%** **FG = < 1%** **LE = 2%** **EB = 23%** **E = 7%**	44,000 yrs
6. **Rapid crack healing (intermittent seismic)**	As above, with episodic Fracture events of 10^{-6} vol. units every 2 kyr	**PG = 67%** **FG = < 1%** **LE = 2%** **EB = 21%** **E = 10%**	75,000 yrs
Observed in field		**PG = 40-50%** **FG = < 2%** **LE = 5-10%** **EB = 25-30%** **E = 15-20%**	